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THE KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING AROMATICS

I - TOLUENE, ETHYLBENZENE, AND p-XYLENE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

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SUMMARY

Knock-limited small-scale-engine tests were made of toluene, ethylbenzene, and p-xylene blended individually in various concentrations with selected base fuels. Data were obtained for the aromatics to determine: (a) the blending sensitivity, (b) the lead susceptibility, and (c) the sensitivity of the blends to inlet-air temperature. Published full-scale-cylinder data for the aromatics are presented for comparative purposes.

The aromatics increased the knock-limited performance of the base fuels at rich fuel-air mixtures. At lean mixture ratios, however, the knock-limited response of the aromatic blends relative to the base fuels was more dependent on the severity of the testing conditions.

INTRODUCTION

In the Organic Synthesis Section of the AERL Fuels and Lubricants Division, a series of aromatics in the C_6 to C_{10} range is being prepared for knock testing. Facilities permit these aromatics to be synthesized or purified to a high state of purity in lots of approximately 10 gallons. When the aromatics are prepared, they are tested in blends with specific base fuels to determine the knock-limited characteristics of these blends. The aromatics that have been prepared at AERL in the first phase of the program are as follows: 1,3,5-trimethylbenzene (mesitylene), m-diethylbenzene, p-xylene, 1-ethyl-4-methylbenzene, tert-butylbenzene, isopropylbenzene (cumene), toluene, ethylbenzene, sec-butylbenzene, benzene, 1,2,4-trimethylbenzene (pseudocumene), and o-xylene.

Because the quantity of each aromatic prepared is small, it is advisable that the research program be so planned that the greatest

amount of useful data can be obtained. Most of the knock testing of pure hydrocarbon compounds has been done in small-scale engines, such as the tests performed at the various industrial laboratories in the CFR engine, at the General Motors Corporation in the General Motors engine under the sponsorship of the American Petroleum Institute, and at the Ethyl Corporation in the 17.6 engine, also under the sponsorship of the American Petroleum Institute.

The data obtained from such tests contain information on the knock-limited power of the pure fuels with and without tetraethyl lead and of the fuels blended in certain base fuels with and without tetraethyl lead. In the past, two procedures have been followed:

(1) The determination of the knock-limited compression ratio (termed the "critical compression ratio") at constant manifold pressure

(2) The determination of the knock-limited manifold pressure and indicated mean effective pressure at constant compression ratio

The data determined by the General Motors Corporation were obtained with the first procedure and those by the Ethyl Corporation with the second procedure. When the test program at AERL was outlined, it was decided to follow the second procedure for most of the tests.

Two factors of primary interest in such tests are the response of the fuels to different engine operating conditions and the response to different engine designs, with particular emphasis on the significance of the results of tests on small-scale engines in relation to those on a full-scale aircraft-engine cylinder. It is desirable that data be obtained under conditions that will correspond to those being used in other laboratories. Three types of engine have been chosen for the tests: the 17.6 engine, the CFR engine, and the R-1820 G200 cylinder. All data on the full-scale cylinder were taken from reference 1.

It is advisable that the base fuels be fuels that are available to all laboratories and that can be reproduced as needed. Two base fuels have been chosen to meet these requirements, S reference fuel and a blend of 85 percent S and 15 percent M reference fuels. The blend of S and M reference fuels is being used as a standard in several laboratories. The use of the 15 percent M in one of the base fuels does not meet the requirement of reproducibility of the fuel but was chosen because this fuel has been used in previous tests (reference 2).

This report, which is the first of a series of five reports presenting test results on aromatic fuels, lists the data on toluene, ethylbenzene and p-xylene. These aromatics were purified by Messrs. T. W. Reynolds and J. I. Wright under the supervision of Dr. L. C. Gibbons. The tests were conducted at the NACA Aircraft Engine Research Laboratory, Cleveland, Ohio, during January and February 1944.

The over-all objectives of the tests consist in determining:

(a) The blending sensitivity of the aromatics in the base reference fuels. These tests were run primarily on three engines.

(b) The lead susceptibility of the aromatic blends. These tests were run on the 17.6 engine, in which blends containing 0 and 4 milliliters tetraethyl lead per gallon were employed.

(c) The temperature sensitivity of the blends of the aromatics in the base fuels. These tests were run on the 17.6 engine at inlet-air temperatures of 250° and 100° F.

(d) The correlation of full-scale and small-scale results.

METHODS OF PRESENTING DATA

Two methods of summarizing the data will be presented in each report. The first method consists in the preparation of a table in which, at each operating condition, the knock-limited indicated mean effective pressures and the knock-limited imep ratios are given at fuel-air ratios of 0.065, 0.070, 0.085, 0.100, and 0.110. The F-3 and F-4 ratings of the blends for which these data are obtained are also tabulated when possible.

The second method of summarizing the data consists in plotting the percentage of specific aromatics in the blend against the knock-limited imep ratios. In these plots the reciprocal scale, which has been used at AERL in analyzing knock-limited data, is sometimes used.

In addition to the summary tables and plots, all experimental data are presented in the conventional form of curves of fuel-air ratio against knock-limited indicated mean effective pressure at the specific test conditions. The knock-limited manifold pressure and the indicated specific fuel consumption under all test conditions are also plotted. The curves of indicated specific fuel consumption are chiefly used as a means of checking the general precision of the

data; no analysis will be made in these reports of the significance of any differences that occur in the data presented.

In the tests made on the CFR engine, ratings (within reference-fuel limits) are given in terms of octane number and S plus milliliters tetraethyl lead or performance number, following the standard procedures for such determinations. The results from tests on the full-scale cylinder (reference 1) are given in terms of S plus M blends or S plus milliters tetraethyl lead. The rating curves of S and S plus milliliters tetraethyl lead are not included in the results on the 17.6 engine because it was believed to be more advisable to use the time available in running tests under different operating conditions rather than under fewer conditions and obtaining the reference-fuel curves. Correlation of the ratings can be obtained, however, through a comparison of the knock-limited imep ratios at the different engine operating conditions and in the different test engines $\left(\text{imep ratio} = \frac{\text{imep of aromatic blend}}{\text{imep of base fuel}}\right)$.

Certain of the aromatics permit knock-limited powers in excess of those that can be represented by the present system of fuel rating; that is, the knock limit of the blends is in excess of that of S plus 6 milliliters tetraethyl lead per gallon. For this reason, imep ratios were recorded in every case.

The temperature sensitivity presented in these reports is expressed as the ratio of the knock-limited indicated mean effective pressure at an inlet-air temperature of 100° F to the knock-limited indicated mean effective pressure at an inlet-air temperature of 250° F as determined on the 17.6 engine. It is recognized that no specific means of expressing temperature sensitivity has been decided upon, but it is believed that the method used herein gives a reasonable indication of temperature sensitivity.

APPARATUS

The 17.6 engine. - The 17.6 engine is a single-cylinder test engine with a stroke of $3\frac{1}{4}$ inches and bore of $2\frac{5}{8}$ inches. The standard inlet manifold of the 17.6 engine was used with its independent "warm-up" fuel system, installed for the purpose of conserving the test fuel. Knock was detected by a cathode-ray oscilloscope in conjunction with a magnetostriction pickup unit.

Because this engine has a small displacement, it permits more data to be obtained with a given amount of fuel than does a larger engine. For this reason, most of the tests have been conducted on the 17.6 engine.

<u>The F-4 engine.</u> - Operation of the research F-4 engine (not a package unit) conformed to CRC designation F-4-443 except for the use of two independent fuel systems and the detection of knock by a cathode-ray oscilloscope in conjunction with a magnetostriction pickup unit. Because of these alterations, the curves of knock-limited indicated mean effective pressure against fuel-air ratio deviates from the F-4 background curves; rich ratings in the research engine, however, are in line with those of a standard F-4 engine. (Hereinafter the research F-4 engine will be referred to as an F-4 engine.)

<u>The F-3 engine.</u> - The F-3 engine conformed to CRC designation F-3-544 with the exception of a barometrically controlled dry-air source in place of a dehydrating ice tower.

TEST PROCEDURE

Each aromatic was blended with S-3 reference fuel in concentrations of 10 and 20 percent by volume; a portion of each blend was leaded to 4 milliliters tetraethyl lead per gallon. In addition, blends were prepared containing 10, 25, and 50 percent by volume of aromatics in the base fuel consisting of 85 percent S-3 plus 15 percent M-4; the final blends contained 4 milliliters tetraethyl lead per gallon. The physical constants of toluene, ethylbenzene, and p-xylene after purification are given in table I.

The choice of engine operating conditions is an important factor in any set of fuel tests. On the 17.6 engine no standardization of test conditions exists. The Ethyl Corporation operates the engine in its laboratory for the American Petroleum Institute at the following conditions:

Engine speed, rpm	900
Compression ratio	5.6
Coolant temperature, °F	300
Inlet-air temperature, °F	225
Spark advance, deg B.T.C.	20

In the NACA tests the 17.6 engine was operated with the following conditions maintained constant:

Engine speed, rpm	1800
Compression ratio	7.0
Outlet-coolant temperature, °F	212
Inlet-air temperature, °F	100, 250
Spark advance, deg B.T.C.	30
Injection timing, deg A.T.C.	60

These conditions were chosen after an examination of results on the antiknock effectiveness of xylidines in the 17.6 engine and three full-scale single-cylinder engines operated at AERL. Two of the full-scale cylinders were of the air-cooled type while the other was liquid cooled.

The operation of the 17.6 engine was checked by daily knock-limited tests on S-3 reference fuel or S-3 plus 4 milliliters tetraethyl lead per gallon. The blending sensitivity of the aromatics in S-3 reference fuel, with or without 4 milliliters tetraethyl lead per gallon, was indicated by comparison of data obtained during the period of 1 day. Lead-susceptibility and temperature-sensitivity checks, however, were made by comparison of tests of different days.

The data on the indicated specific fuel consumption for the blends tested in the 17.6 engine are presented but are intended for use only as control plots and not as an indication of full-scale characteristics of indicated specific fuel consumption.

The CFR engines were run under F-3 and F-4 conditions to obtain results that will correlate with those recorded at other laboratories. In order to permit further correlation of the NACA data with those of other laboratories, the full-scale-cylinder engine was operated under the conditions tentatively recommended by the Coordinating Research Council. The complete description of the tests are on full-scale single-cylinder engine and the data recorded are discussed in more detail in reference 1.

RESULTS AND DISCUSSION

Data on the 17.6 engine. - The knock-limited performance of the blends of toluene, ethylbenzene, and p-xylene in the S-3 base fuel is presented in figures 1 to 6. Aromatic blends were tested clear and with 4 milliliters tetraethyl lead per gallon at inlet-air temperatures of 100° and 250° F.

Certain similarities are evident in the data for the three aromatics. At the high inlet-air temperatures with the unleaded fuel, the knock-limited indicated mean effective pressure was not

appreciably increased through the addition of the aromatics at fuel-air ratios in the neighborhood of 0.065 and 0.070 but was increased at higher fuel-air ratios. When the inlet-air temperature was decreased to 100° F, the knock-limited indicated mean effective pressure at all fuel-air ratios was appreciably increased through the addition of the aromatics. These temperature sensitivities agree with those generally expected of the aromatic fuels.

When tetraethyl lead was added, the data show that even at an inlet-air temperature of 250° F and at the lean mixtures the aromatics increased the knock-limited indicated mean effective pressure of the base fuel, which indicates that the blends were more responsive to the lead additions than was the base fuel. This response of the aromatic blends to the addition of tetraethyl lead was also noted at the lower inlet-air temperature.

In general, the toluene was less effective in increasing the knock-limited indicated mean effective pressure than was either the ethylbenzene or the p-xylene.

Data on the F-4 engine. - Figure 7 presents the F-4 results for the 85 percent S-3 plus 15 percent M-4 base fuel with 4 milliliters tetraethyl lead per gallon. The F-4 results for the three aromatics in blends of 10, 25, and 50 percent are shown in figures 8, 9, and 10 for toluene, ethylbenzene, and p-xylene, respectively. Data for blends of 20 percent of both toluene and ethylbenzene in the S-3 base fuel are also included. With each aromatic, as the concentration was increased, the rich-mixture response increased until, at a concentration of 50 percent, the curve of knock-limited indicated mean effective pressure became nearly vertical in the region of 0.09 to 0.10 fuel-air ratio. Because of engine limitations, the 50-percent blends of these fuels were not tested at fuel-air ratios much in excess of 0.10 nor was it possible to evaluate these rich-mixture responses in terms of S-3 plus lead.

A summation of these knock-limited data is presented in table II, together with the data on the full-scale cylinder (reference 1). Inasmuch as the base fuel was not tested each day in the F-4 engine, an assumed daily knock-limited performance curve of the base fuel was estimated from the performance of the daily bracketing reference fuels and the data of figure 7. These estimated values of the knock-limited power were used in calculating the imep ratios.

In figures 11(a), 12(a), and 13(a) plots of imep ratio against aromatic concentration (linear scale) are presented. These data show the comparative effect of the addition of the aromatics in different concentrations of the knock-limited mean effective pressure

under F-4 conditions at the three fuel-air ratios noted. At lean mixtures (0.070 fuel-air ratio) the knock-limited indicated mean effective pressures showed very little variation with changes in the percentage of the aromatic up to 50 percent. At a fuel-air ratio of 0.085 the knock-limited indicated mean effective pressure increased approximately linearly as the aromatic content was increased. At a fuel-air ratio of 0.10 the rate of increase for a given aromatic concentration increased appreciably as the concentration was increased. The data for ethylbenzene do not show proportionally as great an increase at a fuel-air ratio of 0.10 as do the other two aromatics for the 50-percent blends. This result is due to the fact that the very rapid increase in knock limit caused by the addition of ethylbenzene occurred at fuel-air ratios slightly higher than 0.10.

Figures 11(b), 12(b), and 13(b) present plots of imep ratio (reciprocal scale) against aromatic concentration. The previous data taken on the paraffins blended with the same base fuel (reference 2) showed a linear relation when the indicated mean effective pressure was plotted on the reciprocal scale. This linear relation is not generally applicable to the aromatic blends as tested in the F-4 engine.

Figures 14, 15, and 16 present plots of imep ratio against aromatic concentration on the linear scale for the blends tested in the 17.6 engine. These data show the comparative effect of the addition of aromatics at three fuel-air ratios and also the effect of inlet-air temperature and tetraethyl lead.

The F-3 and the F-4 ratings of the different blends obtained are tabulated in table III. These data are expressed in terms of octane number or S-3 reference fuel plus tetraethyl lead and in terms of performance number.

Table IV contains data on the lead susceptibliity of the blends. In most cases, the lead susceptibility as expressed is greater for the aromatic blends than for the S-3 fuel.

The temperature sensitivities are summarized in table V. With a few exceptions the temperature sensitivity in each case is greater for the aromatic blends than for the base fuel, although as the mixture was enriched the temperature sensitivities of the aromatic blends approached that of the base fuel and at a fuel-air ratio of 0.11 the difference was not great.

In table VI unpublished F-4 engine data for toluene and ethylbenzene from the Universal Oil Products Company are presented and compared with the NACA F-4 engine data. The agreement between the

knock-limited indicated mean effective pressures of the two sets of data was surprisingly good except for those tests wherein knock-limited indicated mean effective pressures of more than 300 pounds per square inch were obtained.

SUMMARY OF RESULTS

From knock-limited tests of fuel blends containing toluene, ethylbenzene, or p-xylene, the following results are presented:

1. Toluene, ethylbenzene, and p-xylene increased the knock-limited indicated mean effective pressures of the two base fuels in the rich region at all operating conditions tested. The amount of increase varied from 5 to 183 percent depending on the operating conditions and the percentage of aromatics. p-Xylene allowed greater knock-limited indicated mean effective pressures at high fuel-air ratios than did either toluene or ethylbenzene, but in some cases the differences were small.

2. At lean fuel-air mixtures, the following results were noted:

(a) The three aromatics increased the knock-limited indicated mean effective pressures of the base fuel 10 to 39 percent in the full-scale cylinder.

(b) In the 17.6 engine the addition of the aromatics increased the knock-limited indicated mean effective pressures of the base fuel from 0 to 33 percent.

(c) In the F-4 engine the effect of the aromatics varied from an increase of 9 percent to a decrease of 6 percent in the knock-limited indicated mean effective pressure of the base fuel.

(d) In the F-3 engine the aromatics decreased the knock rating in nearly all cases.

3. Though some exceptions were noted, the general trend indicated that the lead susceptibility of the aromatic blends increased with increasing aromatic content and decreased with increasing inlet-air temperature.

4. In general, the knock-limited performance of the aromatic blends was more susceptible to changes in inlet-air temperature than was the S-3 reference fuel.

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REFERENCES

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2. Puckett, Afton D., and Brooks, Donald B.: Supercharged CFR Engine Tests of Twelve Pure Hydrocarbons. Special Rep. No. 11, Nat. Bur. Standards Hydrocarbon Fuel Res. Lab., Sept. 17, 1943.

TABLE I. - PHYSICAL CONSTANTS OF TOLUENE, ETHYLBENZENE, AND p-XYLENE

Aromatic	Freezing point (°C)	Boiling point (°C)	Index of refraction n_D^{20}	Density at 20° C (gram/ml)
Toluene	-95.014	110.6	1.4967	0.8668
Ethylbenzene	-95.025	136.2	1.4960	.8664
p-Xylene	13.228	138.4	1.4960	.8605

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TABLE II. - SUPERCHARGED-ENGINE TESTS OF BLENDS CONTAINING TOLUENE, ETHYLBENZENE, OR p-XYLENE

Fuel composition					Engine conditions		Test results									
Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	Engine speed (rpm)	Inlet-air temperature (°F)	Fuel-air ratio									
							0.065		0.070		0.085		0.100		0.110	
	Pure aromatic	S-3 reference fuel	85 percent S-3 plus 15 percent M-4				imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]
17.6 engine																
Toluene	10	90	0	0	1800	250	138	1.04	137	1.02	158	1.05	176	1.08	181	1.11
Ethylbenzene	10	90	0	0			136	1.02	137	1.02	159	1.04	185	1.11	193	1.16
p-Xylene	10	90	0	0			136	1.01	136	1.01	167	1.10	187	1.12	191	1.14
Toluene	20	80	0	0	1800	250	138	1.04	137	1.02	166	1.11	197	1.21	206	1.26
Ethylbenzene	20	80	0	0			135	1.02	134	1.00	164	1.07	200	1.21	219	1.31
p-Xylene	20	80	0	0			140	1.04	140	1.04	176	1.16	213	1.28	231	1.38
Toluene	20	80	0	0	1800	100	170	1.05	173	1.07	201	1.18	215	1.21	218	1.24
Ethylbenzene	20	80	0	0			196	1.19	199	1.21	221	1.28	237	1.35	238	1.36
p-Xylene	20	80	0	0			196	1.15	202	1.20	225	1.29	240	1.34	248	1.40
Toluene	10	90	0	4	1800	250	218	1.01	229	1.03	258	1.04	273	1.05	285	1.10
Ethylbenzene	10	90	0	4			229	1.07	237	1.07	263	1.08	282	1.10	291	1.13
p-Xylene	10	90	0	4			222	1.04	239	1.08	274	1.12	293	1.14	300	1.16
Toluene	20	80	0	4	1800	250	227	1.05	239	1.07	276	1.11	308	1.19	327	1.26
Ethylbenzene	20	80	0	4			243	1.14	259	1.17	297	1.22	336	1.31	351	1.36
p-Xylene	20	80	0	4			225	1.05	250	1.13	301	1.23	343	1.34	364	1.41
Toluene	20	80	0	4	1800	100	309	1.13	317	1.17	342	1.23	362	1.29	365	1.31
Ethylbenzene	20	80	0	4			348	1.29	359	1.33	379	1.36	383	1.37	381	1.38
p-Xylene	20	80	0	4			334	1.23	348	1.28	397	1.42	412	1.47	412	1.48
F-4 engine																
Toluene	10	0	90	4	1800	225	139	1.01	154	1.05	181	1.08	194	1.10	197	1.13
Ethylbenzene	10	0	90	4			145	1.06	157	1.07	185	1.11	198	1.12	200	1.14
p-Xylene	10	0	90	4			128	1.04	143	1.07	178	1.10	192	1.10	194	1.11
Toluene	25	0	75	4	1800	225	137	1.00	153	1.04	197	1.18	227	1.29	240	1.37
Ethylbenzene	25	0	75	4			140	1.02	159	1.08	202	1.21	227	1.29	240	1.37
p-Xylene	25	0	75	4			124	1.01	146	1.09	205	1.28	243	1.39	262	1.50
Toluene	50	0	50	4	1800	225	115	0.84	146	0.99	212	1.27	428	2.43	---	----
Ethylbenzene	50	0	50	4			119	.99	142	1.07	227	1.44	297	1.71	---	----
p-Xylene	50	0	50	4			115	.94	138	1.03	252	1.57	495	2.83	---	----
Full-scale cylinder (reference 1)																
Toluene	25	0	75	4	2000	210	190	1.28	196	1.30	258	1.41	317	1.48	323	1.42
Ethylbenzene	25	0	75	4			200	1.35	210	1.39	265	1.45	296	1.38	306	1.35
p-Xylene	25	0	75	4			183	1.24	198	1.31	307	1.68	345	1.61	358	1.58
Toluene	25	0	75	4	2500	250	170	1.10	176	1.12	262	1.41	302	1.40	320	1.38
Ethylbenzene	25	0	75	4			174	1.12	192	1.22	249	1.33	294	1.36	309	1.34
p-Xylene	25	0	75	4			184	1.19	190	1.21	290	1.55	354	1.64	380	1.64

[a] $\text{imep ratio} = \dfrac{\text{imep of aromatic blend}}{\text{imep of base fuel}}$. For those blends tested in the 17.6 engine, the base fuel is S-3 or S-3 plus 4 ml TEL/gal; in all other instances, the base fuel is 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL/gal.

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TABLE III. - F-4 AND F-3 RATINGS OF TOLUENE, ETHYLBENZENE, AND p-XYLENE BLENDS

Compound	Composition (percent by volume)			Tetraethyl lead (ml/gal)	F-4 ratings				F-3 ratings	
					Lean		Rich			
	Pure aromatic	S-3 reference fuel	85 percent S-3 plus 15 percent M-4		S-3 + ml TEL	Performance number	S-3 + ml TEL	Performance number	S-3 + ml TEL	Performance number
Base fuel	0	0	100	4	0.36	112	0.26	109	0.39	113
Toluene	10	0	90	4	0.46	114	0.89	124	0.44	114
Ethylbenzene	10	0	90	4	.63	119	1.02	126	.42	113
p-Xylene	10	0	90	4	.50	115	1.03	126	.61	116
Toluene	25	0	75	4	0.34	111	3.85	152	0.34	111
Ethylbenzene	25	0	75	4	.50	115	4.36	154	.40	113
p-Xylene	25	0	75	4	.35	111	6.00	161	.53	120
Toluene	50	0	50	4	0.08	103	>6.00	———	0.28	110
Ethylbenzene	50	0	50	4	.37	112	>6.00	———	.07	103
p-Xylene	50	0	50	4	.20	107	>6.00	———	———	———
p-Xylene	10	90	0	4	———	———	———	———	3.24	148
Toluene	20	80	0	4	2.48	143	>6.00	———	2.07	139
Ethylbenzene	20	80	0	4	2.06	139	>6.00	———	1.97	138
p-Xylene	20	80	0	4	———	———	———	———	1.97	138
Ethylbenzene	10	90	0	0	———	———	———	———	[a]99.2	99
p-Xylene	10	90	0	0	———	———	———	———	[a]99.5	99
Toluene	20	80	0	0	———	———	———	———	[a]98.3	97
Ethylbenzene	20	80	0	0	———	———	———	———	[a]98.6	98
p-Xylene	20	80	0	0	———	———	———	———	[a]99.6	99

[a]Octane number.

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TABLE IV. - LEAD SUSCEPTIBILITY OF TOLUENE, ETHYLBENZENE, AND p-XYLENE BLENDS

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; outlet-coolant temperature, 212° F; spark advance, 30° B.T.C.]

Compound	Inlet-air temperature (°F)	Composition (percent by volume)		$\frac{\text{imep, with 4 ml TEL/gal}}{\text{imep, with 0 ml TEL/gal}}$				
		Pure aromatic	S-3 reference fuel	Fuel-air ratio				
				0.065	0.070	0.085	0.100	0.110
[a]S-3	250	0	100	1.60	1.64	1.62	1.56	1.55
Toluene	250	10	90	1.58	1.67	1.63	1.55	1.57
Ethylbenzene	250	10	90	1.68	1.73	1.65	1.52	1.51
p-Xylene	250	10	90	1.63	1.76	1.64	1.57	1.57
Toluene	250	20	80	1.64	1.74	1.66	1.56	1.59
Ethylbenzene	250	20	80	1.80	1.93	1.81	1.68	1.60
p-Xylene	250	20	80	1.61	1.79	1.71	1.61	1.58
[a]S-3	100	0	100	1.64	1.64	1.62	1.57	1.58
Toluene	100	20	80	1.82	1.83	1.70	1.68	1.67
Ethylbenzene	100	20	80	1.78	1.80	1.71	1.62	1.60
p-Xylene	100	20	80	1.70	1.72	1.76	1.72	1.66

[a]The values presented for S-3 were obtained by averages from the curves for S-3 and the curves for S-3 plus 4 ml TEL/gal.

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TABLE V. - TEMPERATURE SENSITIVITY OF TOLUENE, ETHYLBENZENE, AND p-XYLENE BLENDS

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; outlet-coolant temperature, 212° F; spark advance, 30° B.T.C.]

Compound	Composition (percent by volume)		Tetraethyl lead (ml/gal)	$\frac{\text{imep, inlet-air temp., } 100^\circ \text{ F}}{\text{imep, inlet-air temp., } 250^\circ \text{ F}}$				
	Pure aromatic	S-3 reference fuel		Fuel-air ratio				
				0.065	0.070	0.085	0.100	0.110
[a]S-3	0	100	0	1.24	1.22	1.13	1.08	1.06
Toluene	20	80	0	1.23	1.26	1.21	1.09	1.06
Ethylbenzene	20	80	0	1.45	1.49	1.35	1.18	1.09
p-Xylene	20	80	0	1.40	1.44	1.28	1.13	1.07
[a]S-3	0	100	4	1.27	1.22	1.13	1.09	1.08
Toluene	20	80	4	1.36	1.33	1.24	1.18	1.12
Ethylbenzene	20	80	4	1.43	1.39	1.28	1.14	1.09
p-Xylene	20	80	4	1.48	1.39	1.32	1.20	1.13

[a]The values presented for S-3 were obtained by using averages from the S-3 curves at the two inlet-air temperatures.

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TABLE VI. - A COMPARISON OF NACA AND UNIVERSAL OIL PRODUCTS COMPANY

DATA FOR TOLUENE AND ETHYLBENZENE BLENDS

[F-4 engine; final blends contain 4 ml TEL/gal]

Compound	Composition (percent by volume)		Source of data	imep, lb/sq in.						
				Fuel-air ratio						
	Aromatic	85 percent S-3 + 15 percent M-4		0.070	0.080	0.090	0.095	0.100	0.110	0.120
Base fuel	0	100	NACA	147	162	172	174	175	175	170
			UOP	144	[illegible]	174	176	180	181	180
Toluene	10	90	NACA	154	174	137	191	194	197	196
			UOP	146	172	186	192	195	203	202
Toluene	25	75	NACA	153	184	209	220	227	240	249
			UOP	142	183	209	221	230	237	238
Toluene	50	50	NACA	146	195	243	299	428	—	—
			UOP	136	174	268	295	310	333	350
Ethylbenzene	10	90	NACA	157	177	191	195	198	200	197
			UOP	142	178	193	196	197	201	202
Ethylbenzene	25	75	NACA	159	191	211	219	227	240	253
			UOP	130	173	200	211	222	235	246
Ethylbenzene	50	50	NACA	142	204	250	272	297	—	—
			UOP	136	215	262	280	293	325	—

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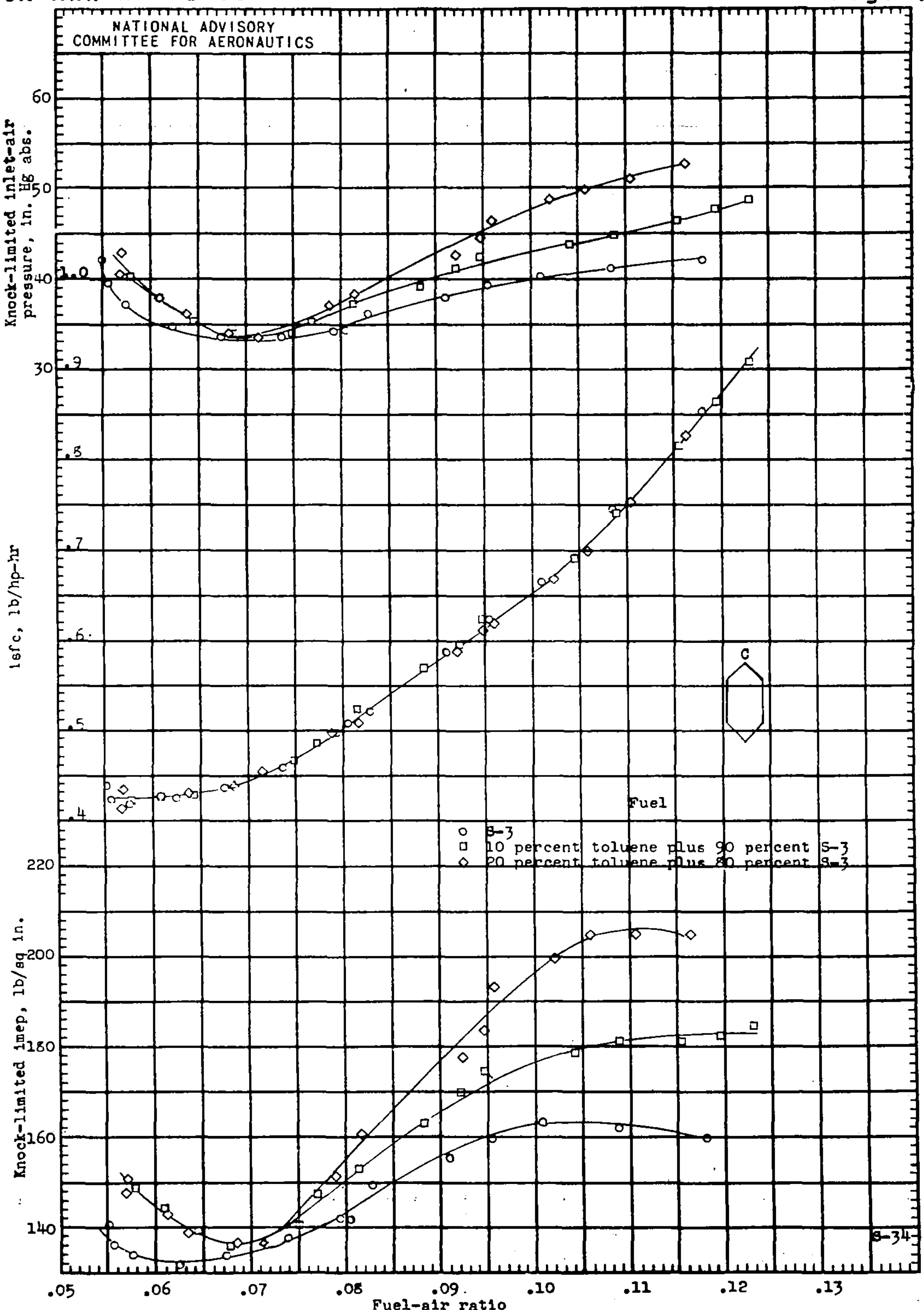
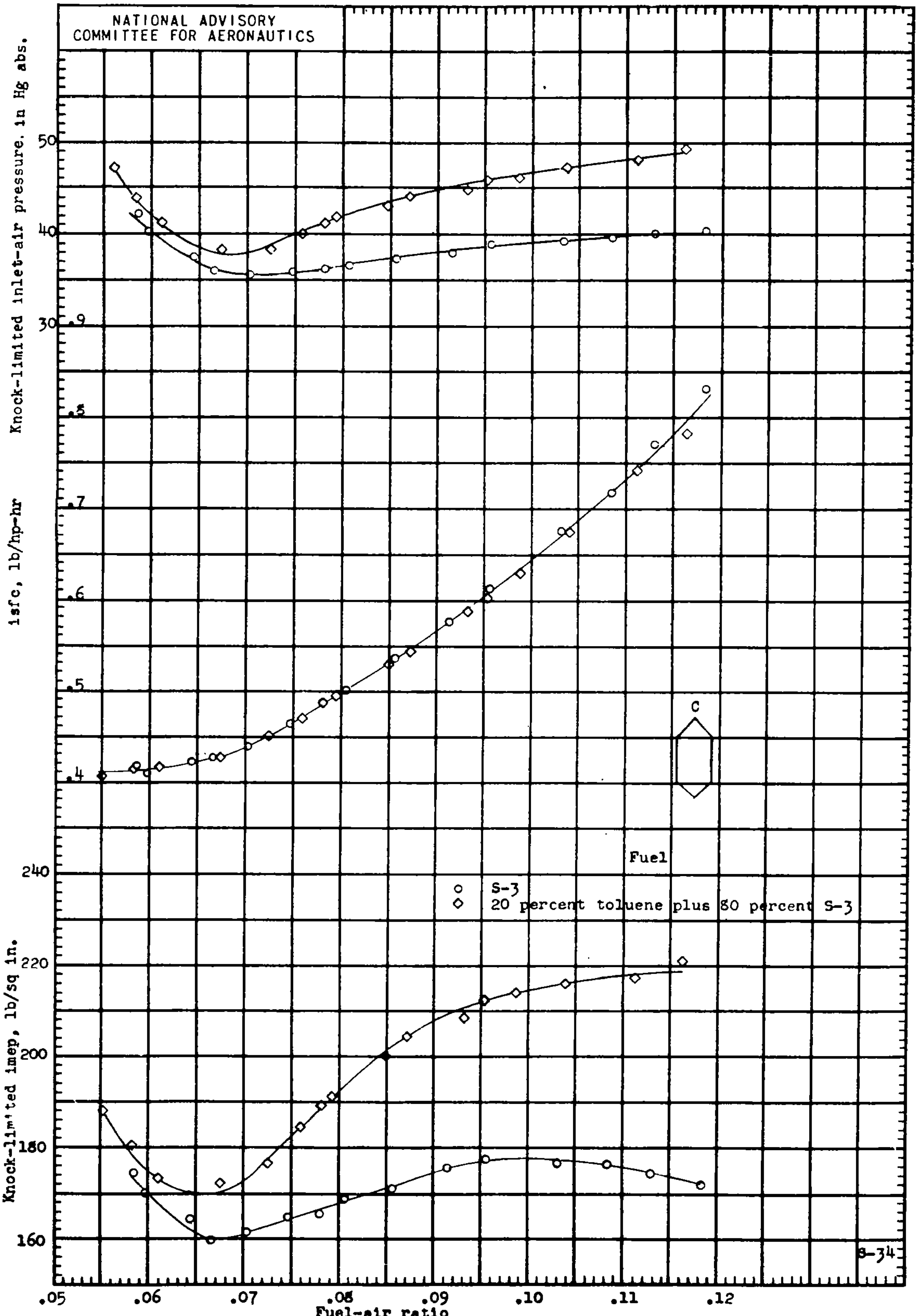
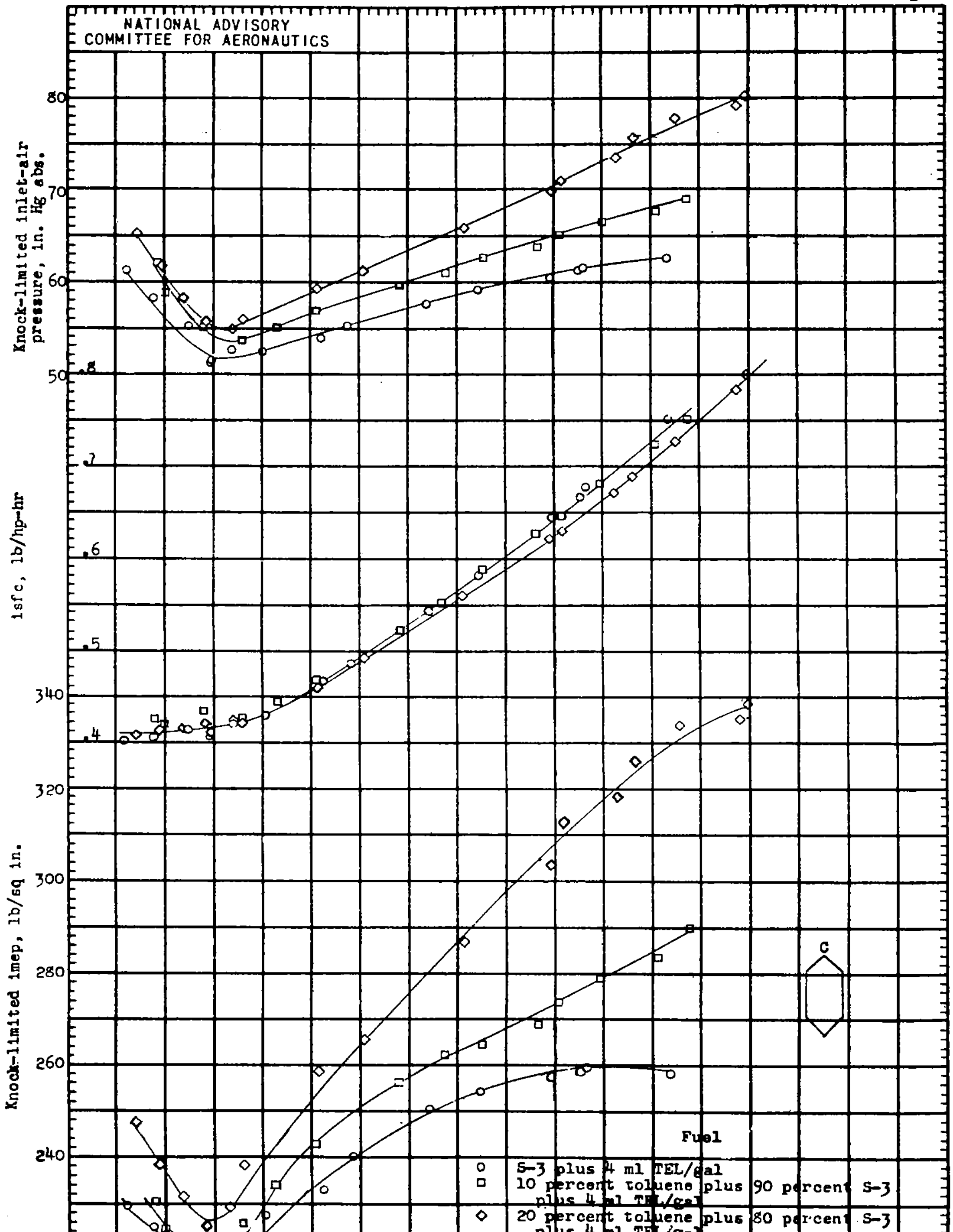


(a) Inlet-air temperature, 250° F.

Figure 1. - Knock-limited performance of blends of toluene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

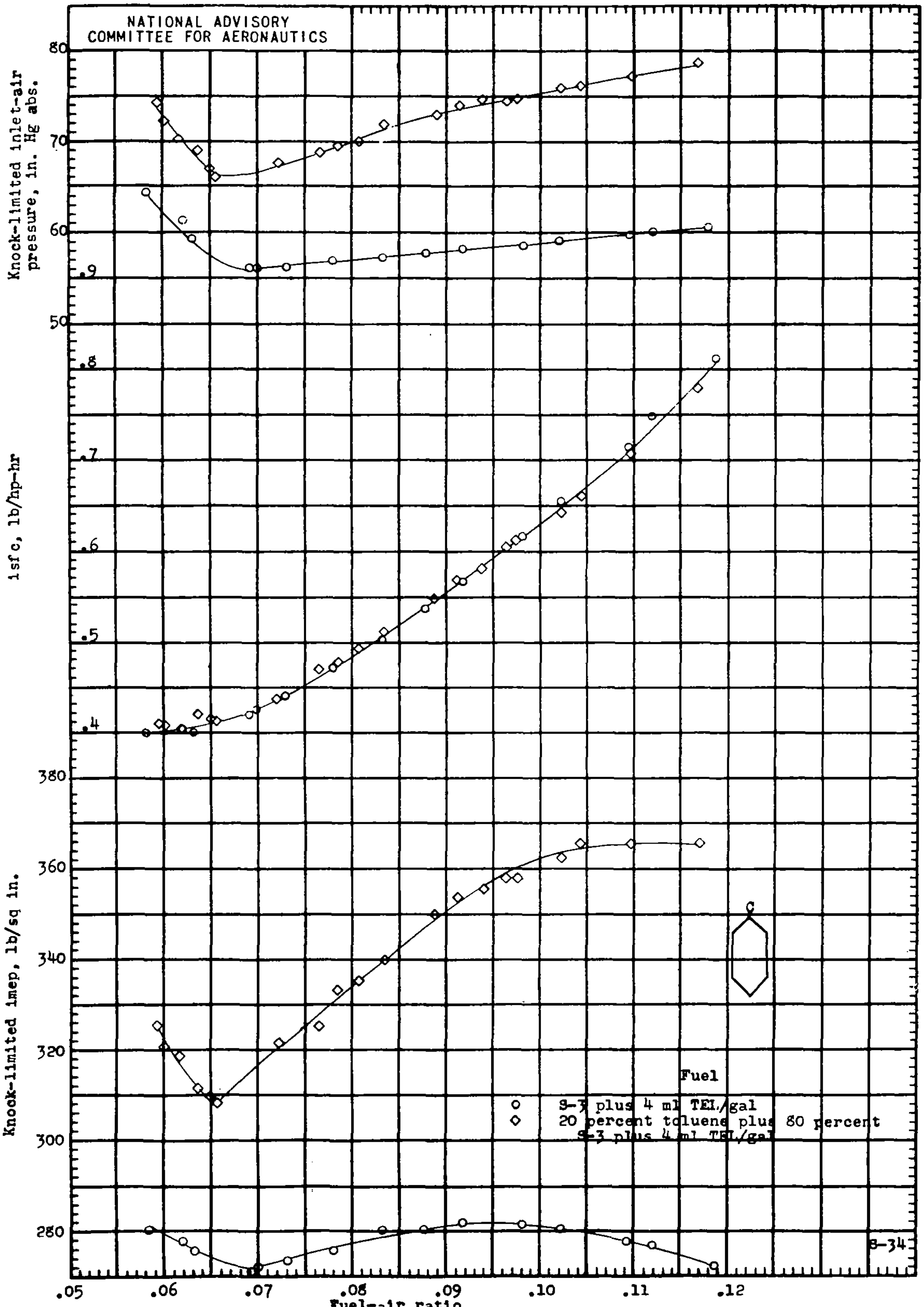


(b) Inlet-air temperature, 100° F.
Figure 1. - Concluded.

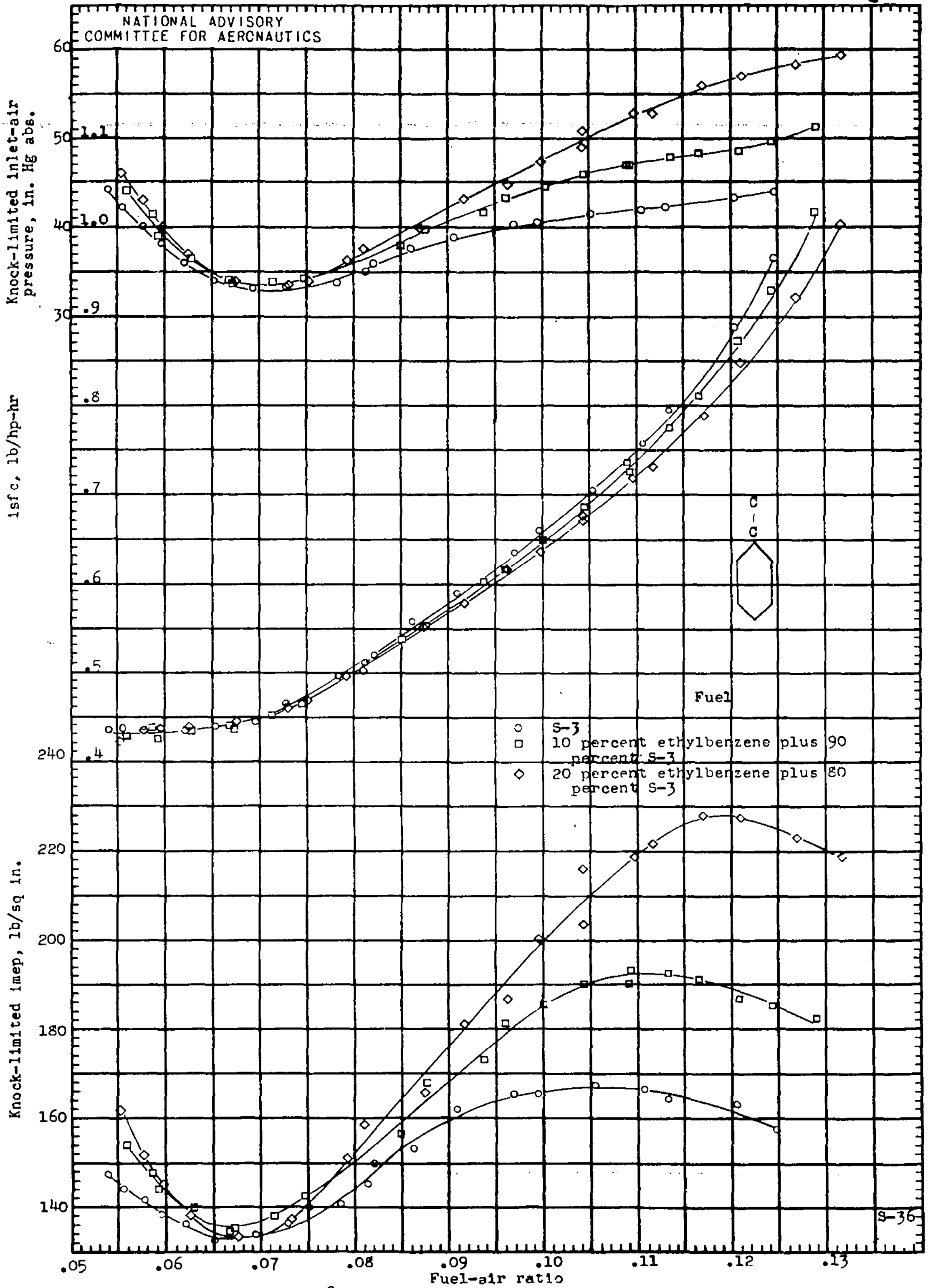


(a) Inlet-air temperature, 250° F.

Figure 2. - Knock-limited performance of blends of toluene and S-3 reference fuel plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

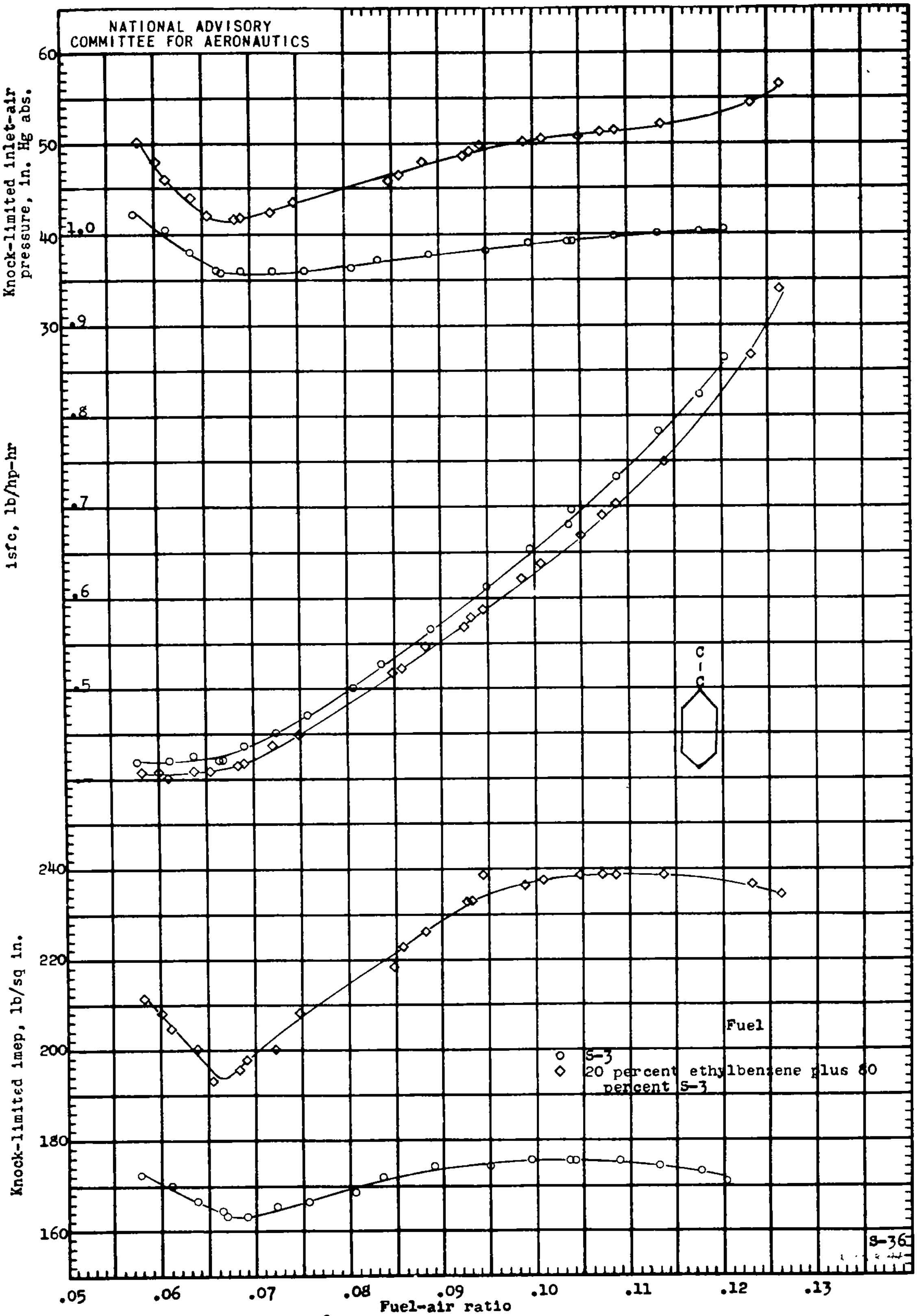


(b) Inlet-air temperature, 100° F.
Figure 2. - Concluded.

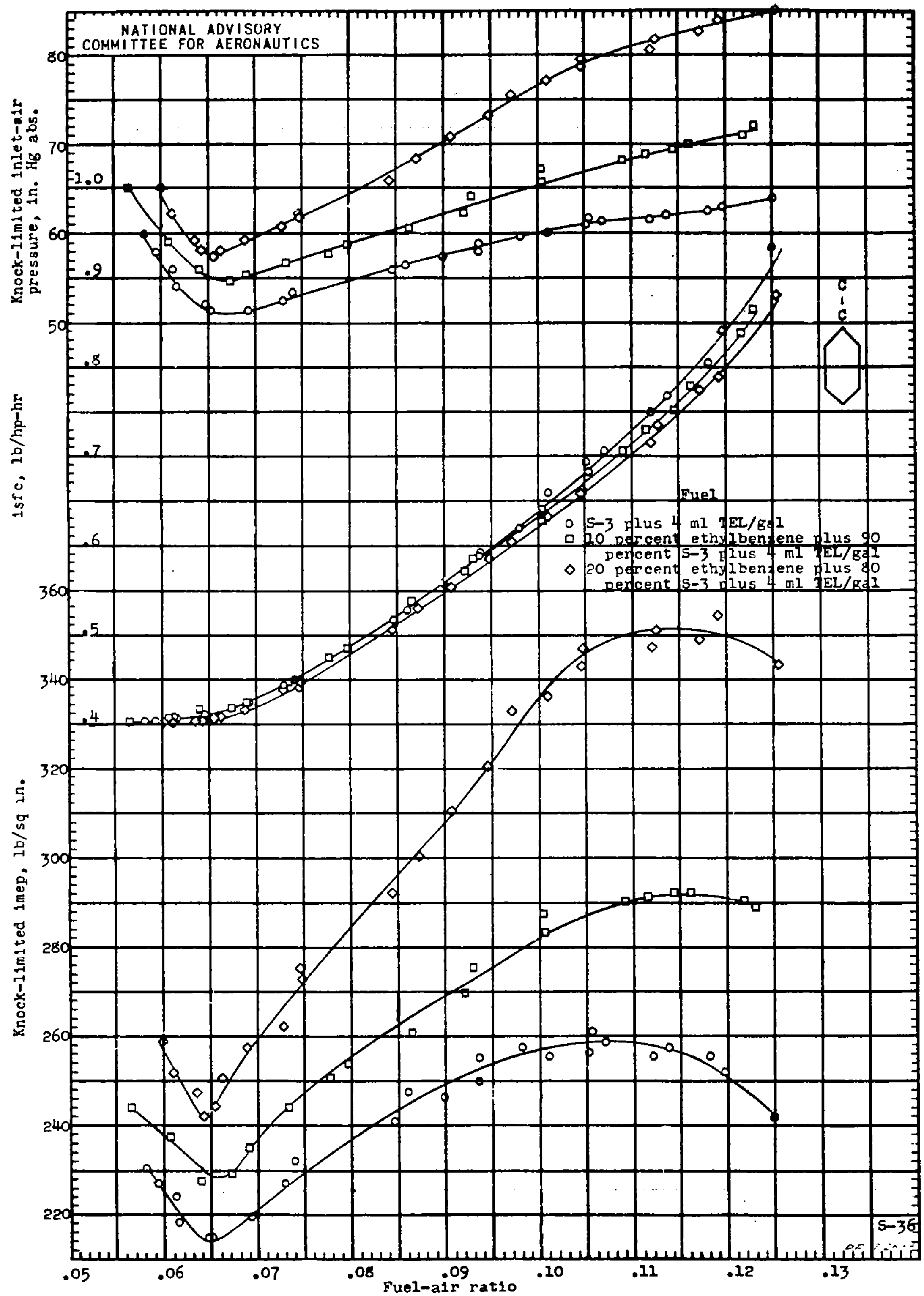


(a) Inlet-air temperature, 250° F.

Figure 3. - Knock-limited performance of blends of ethylbenzene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

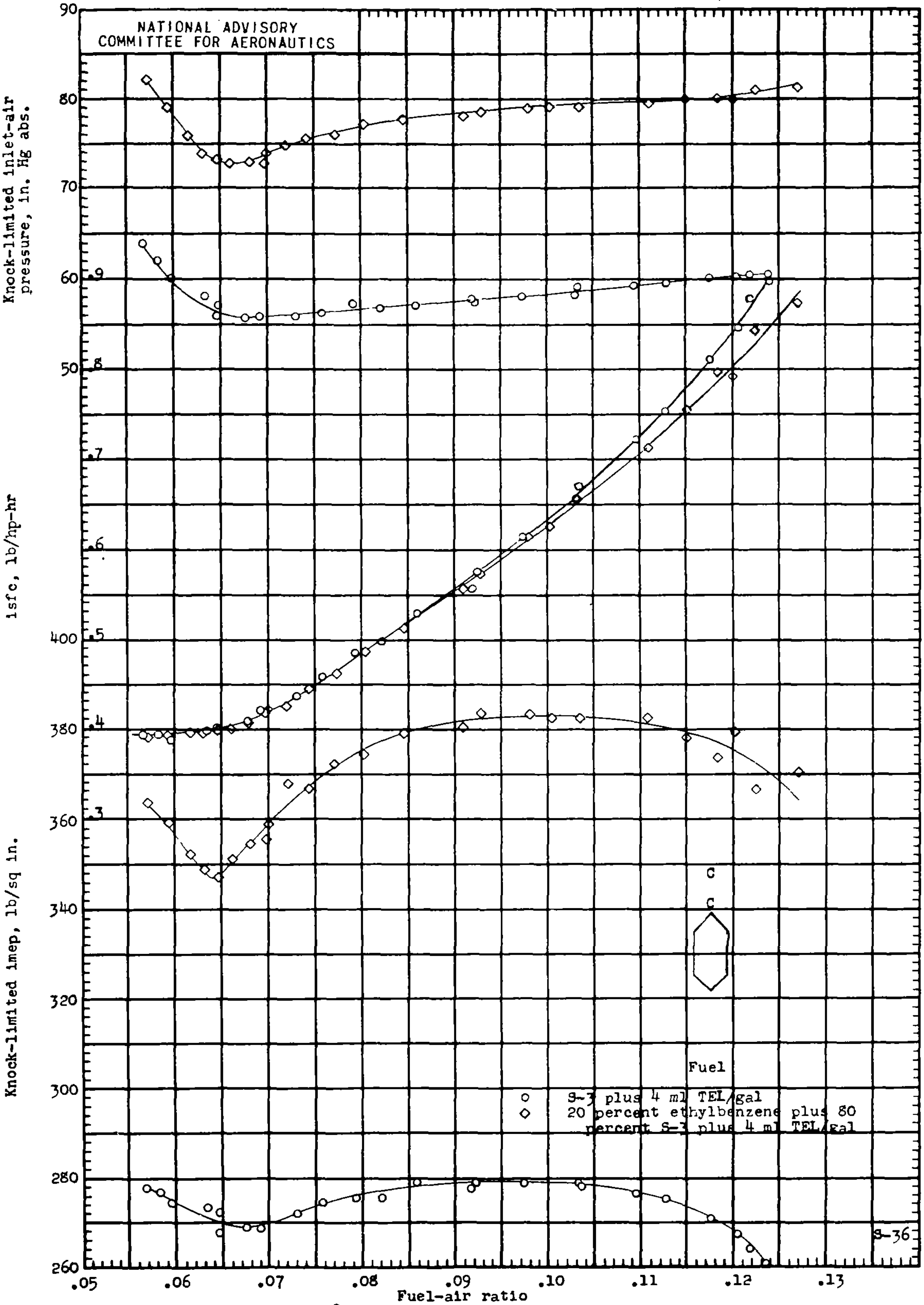


(b) Inlet-air temperature, 100° F.
Figure 3. - Concluded.

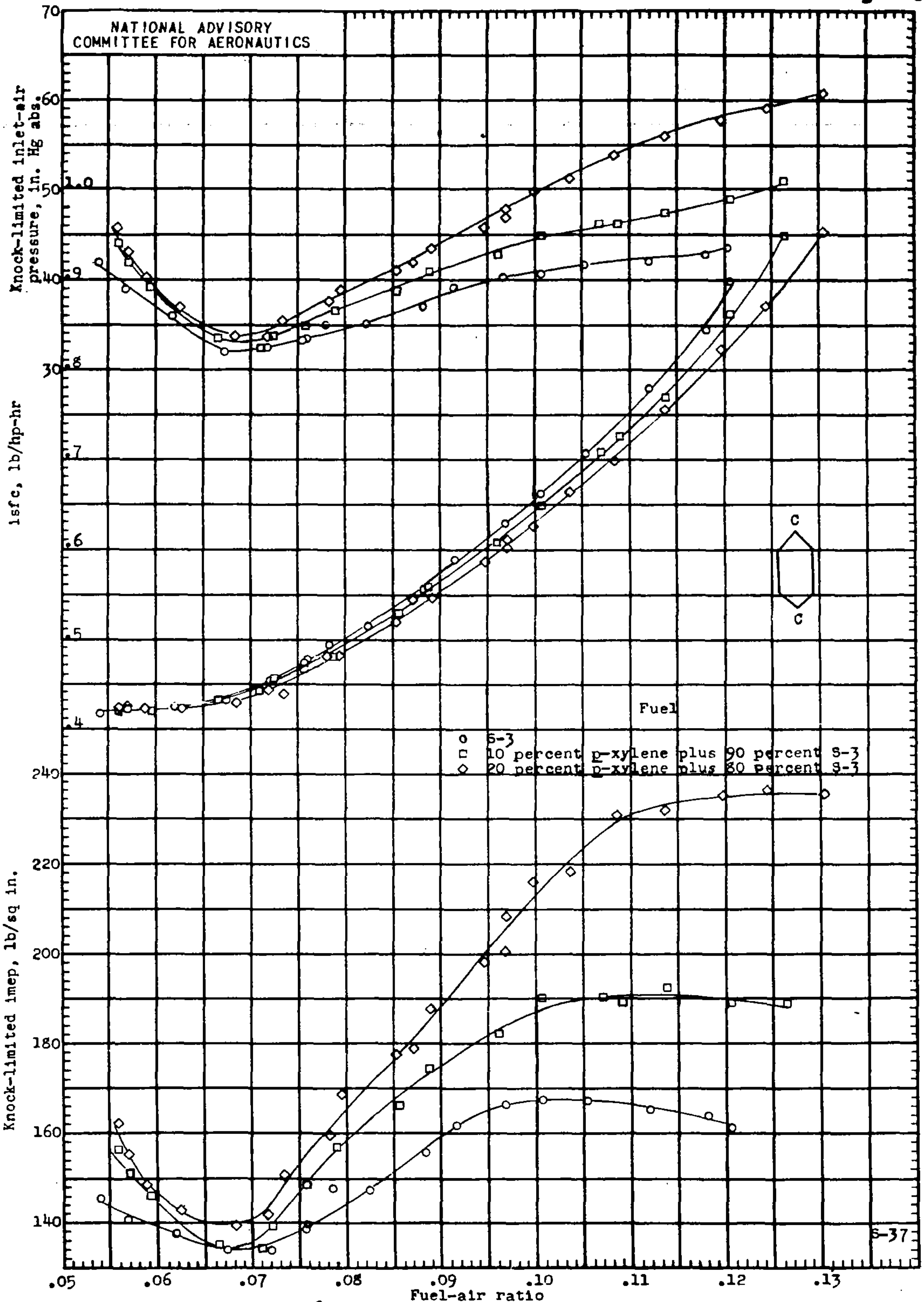


(a) Inlet-air temperature, 250° F.

Figure 4. - Knock-limited performance of blends of ethylbenzene and S-3 reference fuel plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

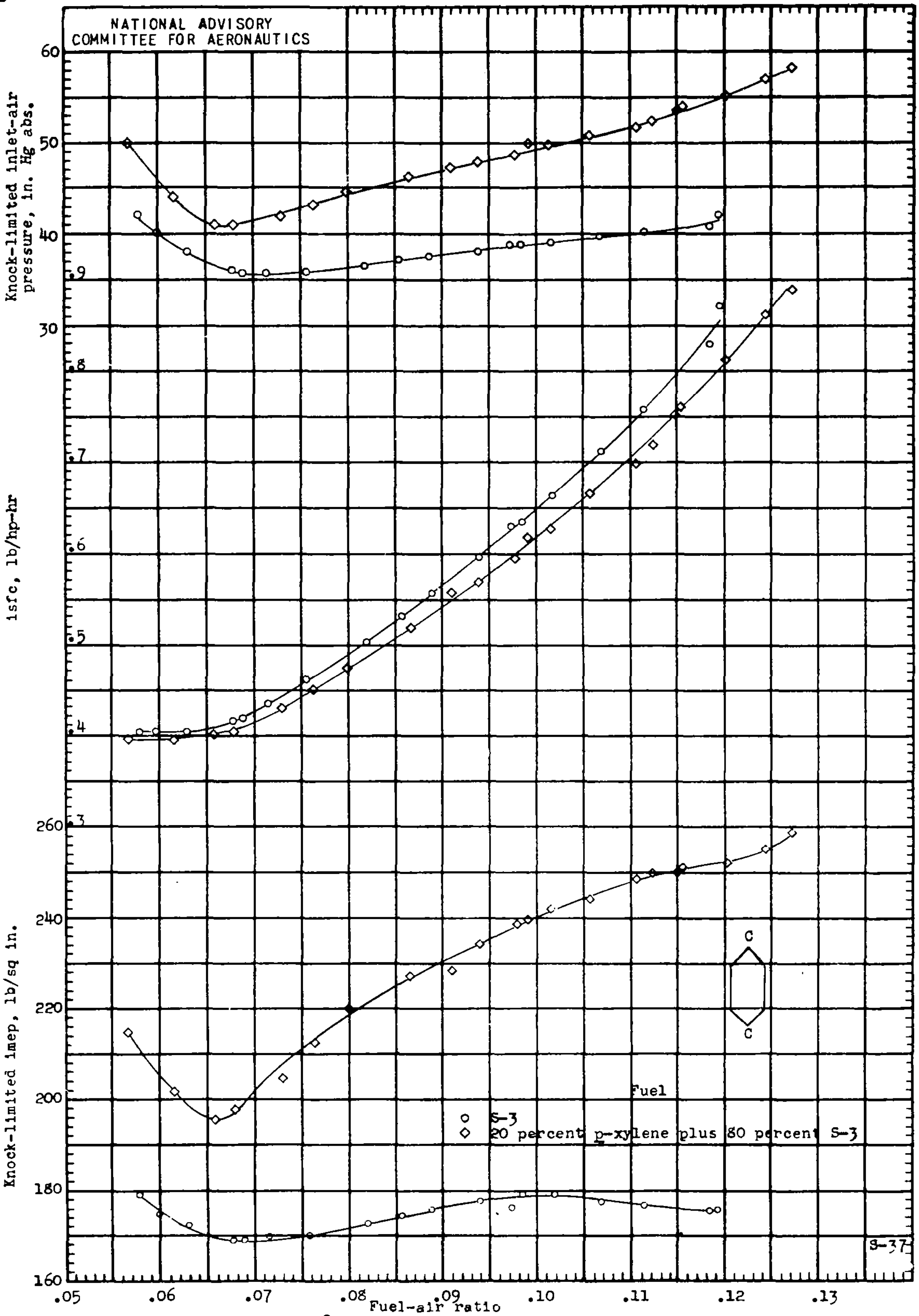


(b) Inlet-air temperature, 100° F.
Figure 4. - Concluded.

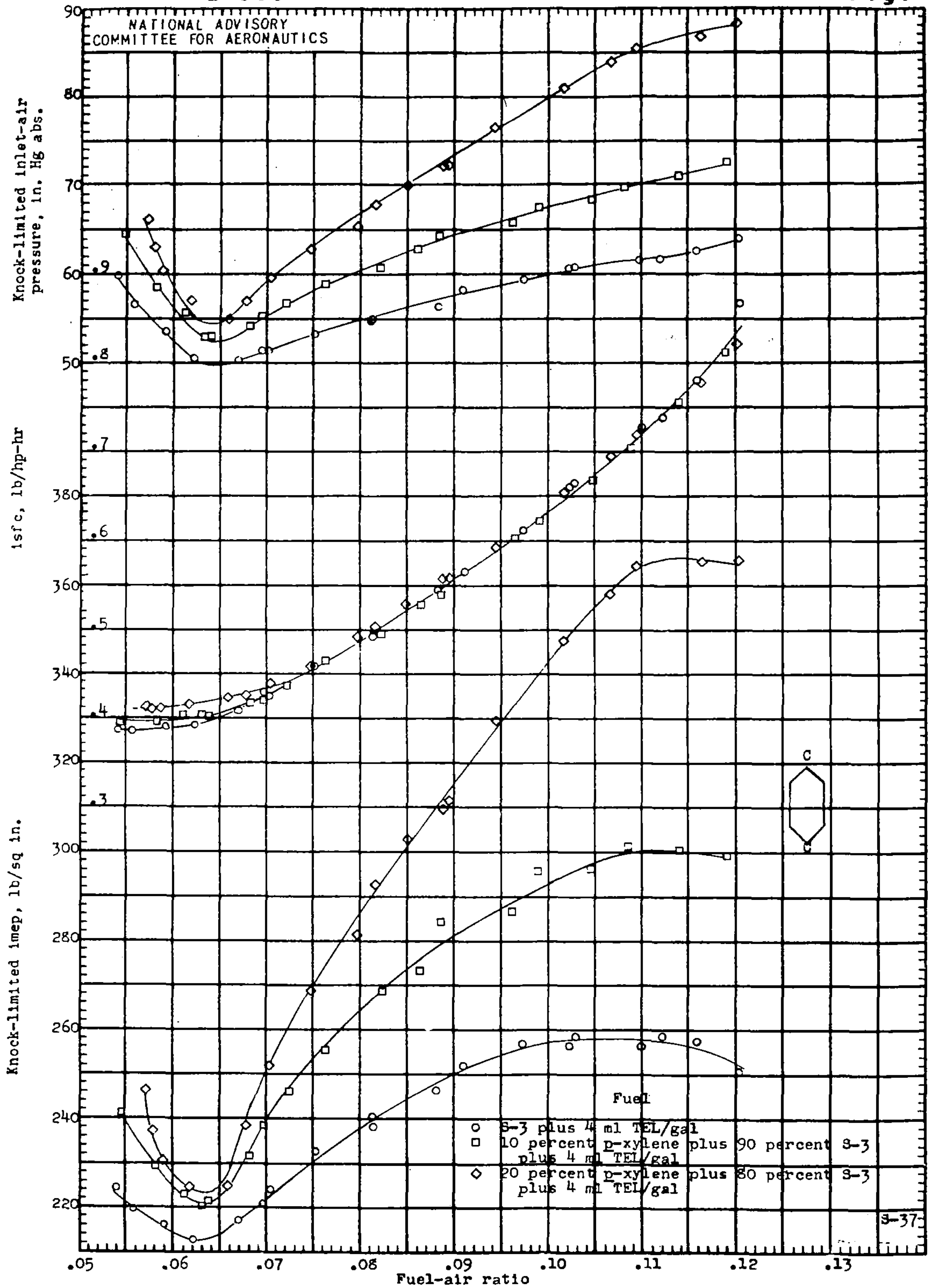


(a) Inlet-air temperature, 250° F.

Figure 5. - Knock-limited performance of blends of p-xylene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

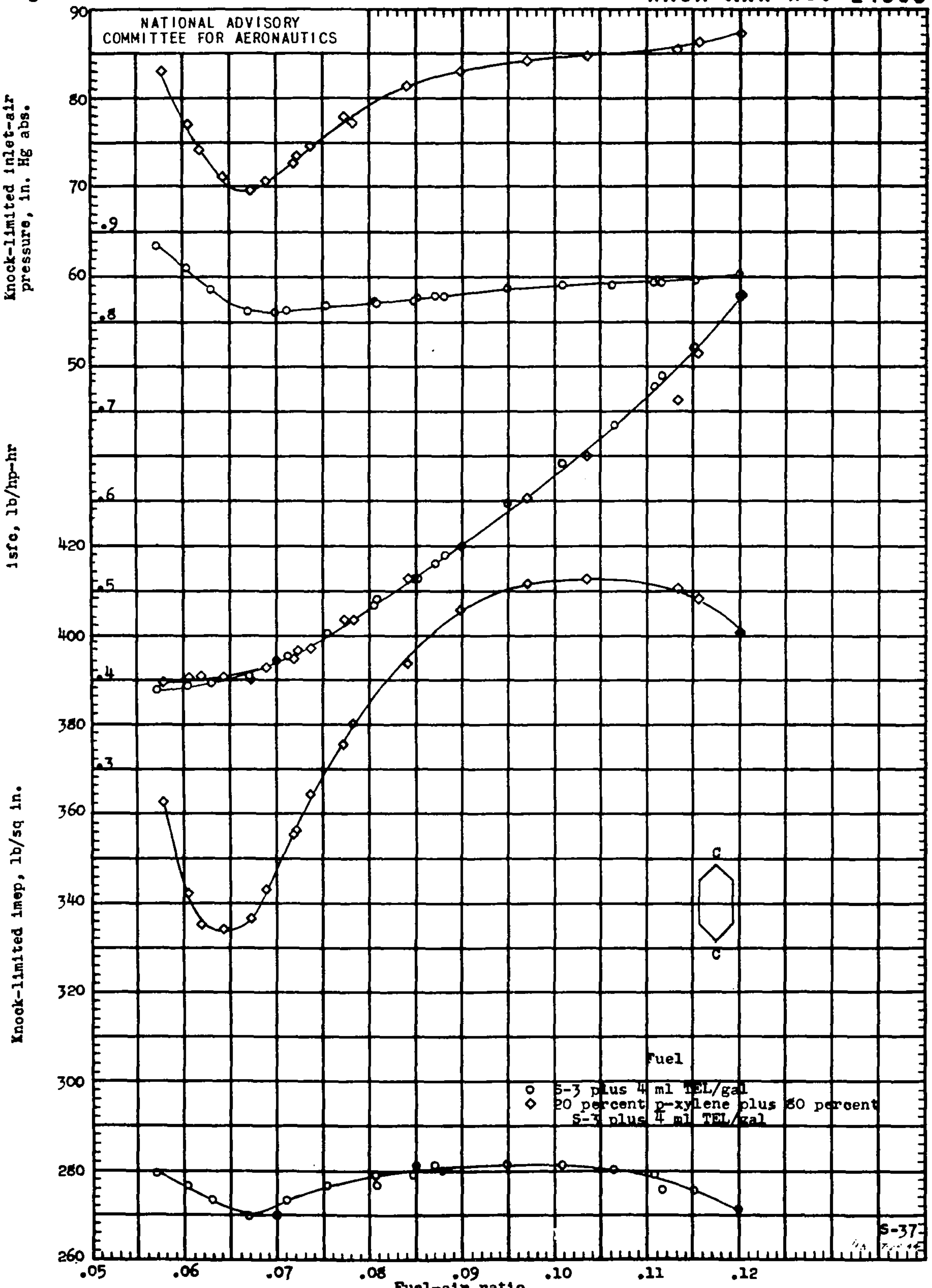


(b) Inlet-air temperature, 100° F.
Figure 5. - Concluded.



(a) Inlet-air temperature, 250° F.

Figure 6. - Knock-limited performance of blends of p-xylene and S-3 reference fuel plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.



(b) Inlet-air temperature, 100° F.
Figure 6. - Concluded.

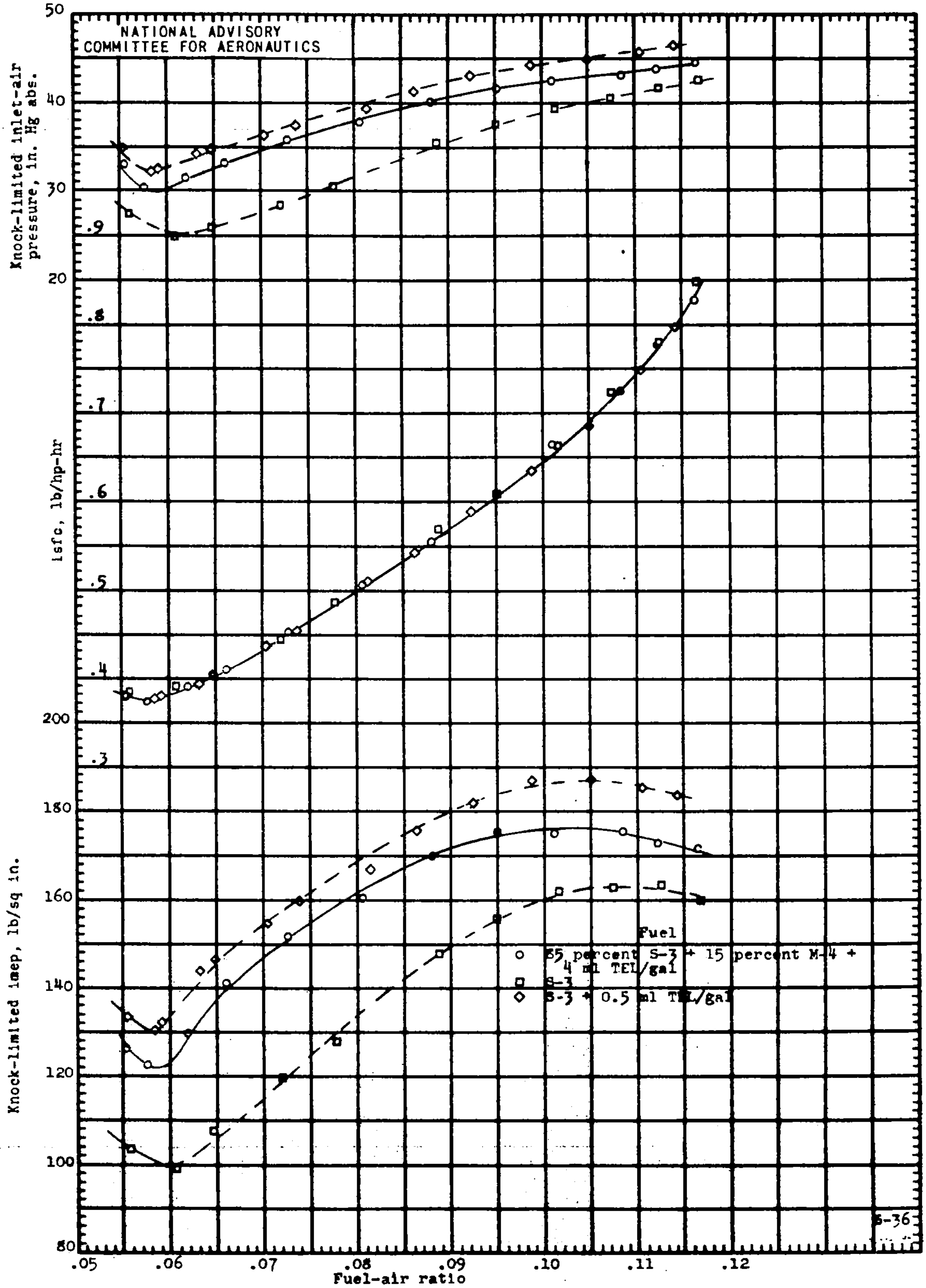
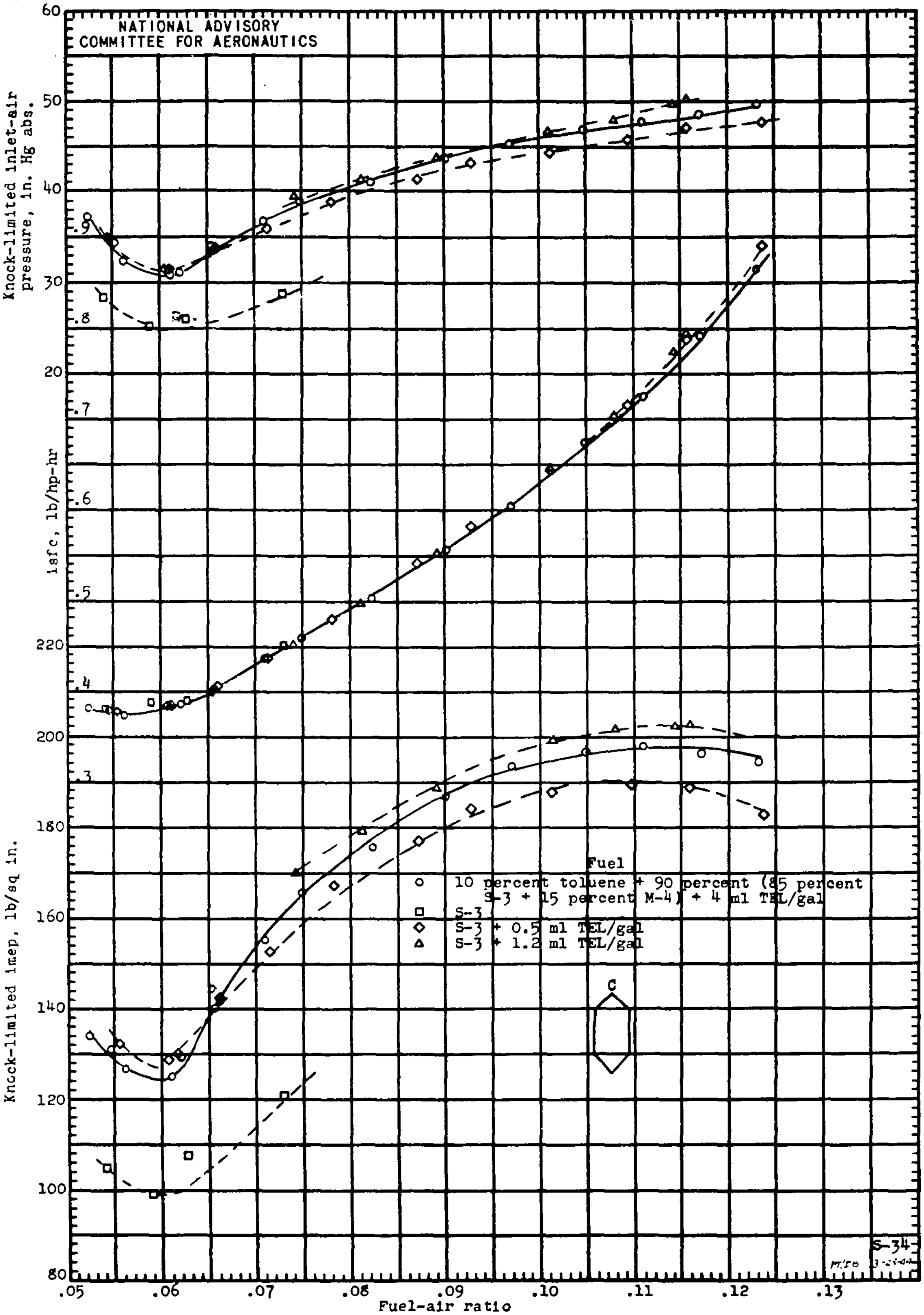
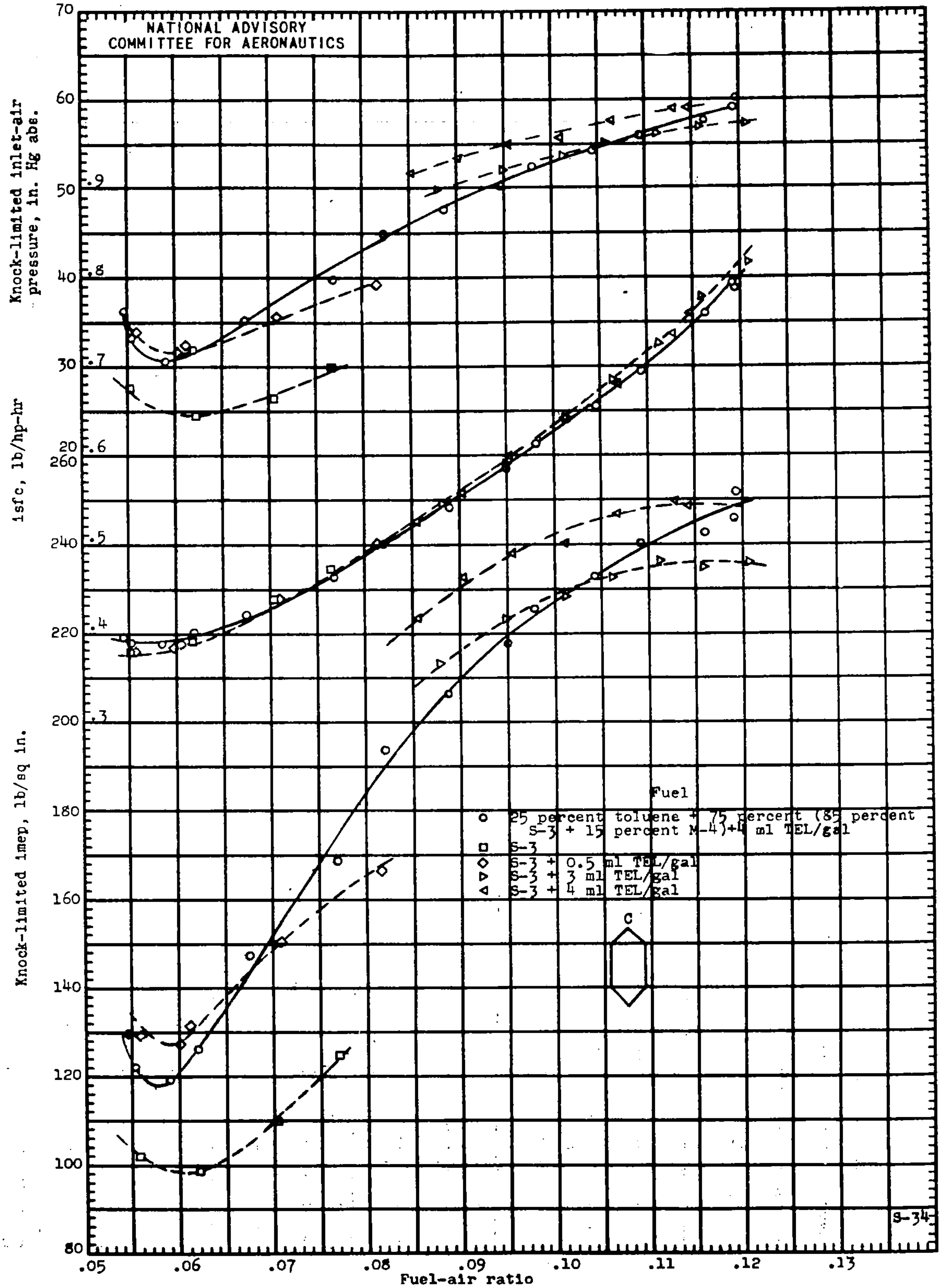


Figure 7. - Knock-limited performance of 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon in an F-4 engine.



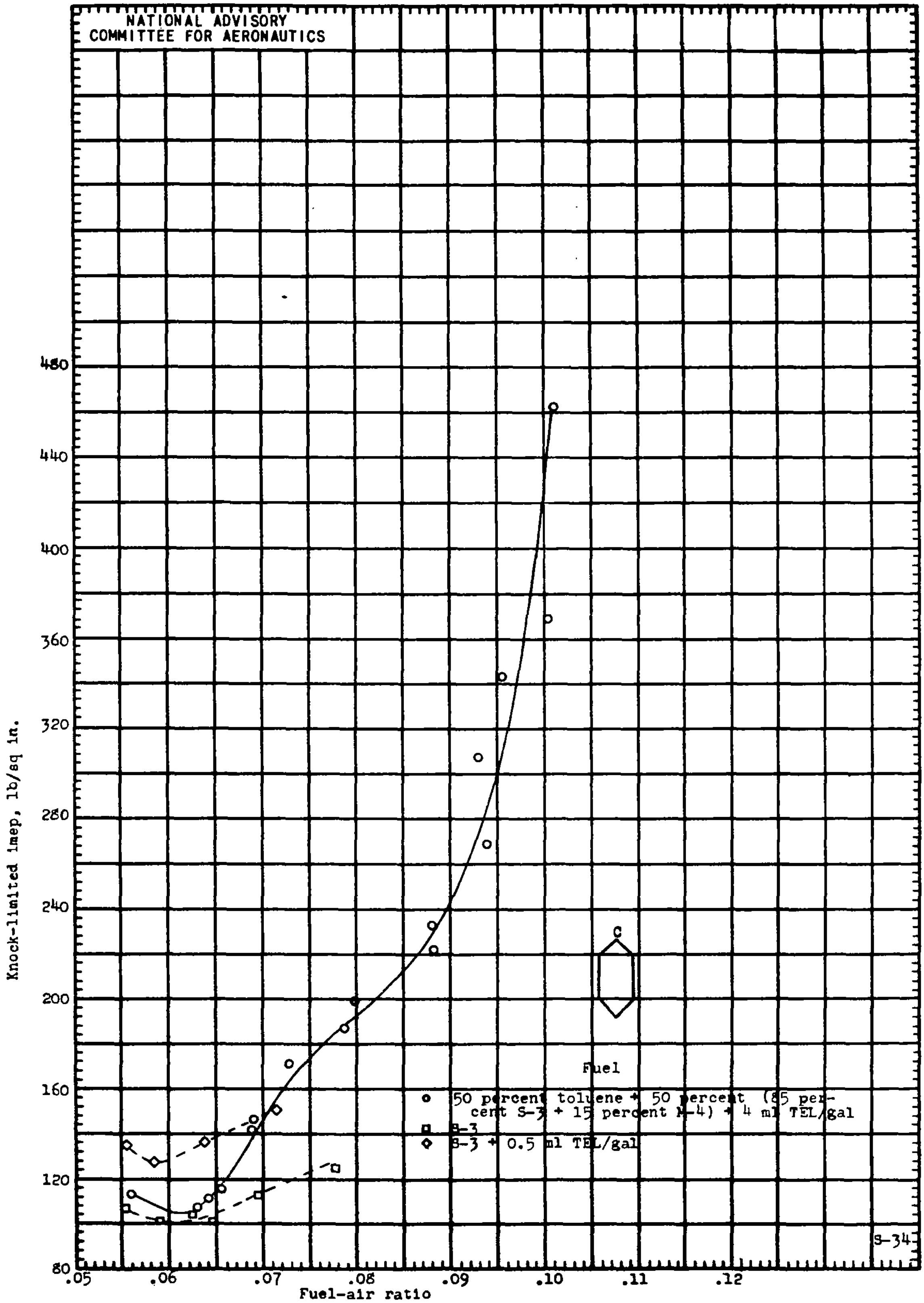
(a) 10 percent toluene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 8. - Knock-limited performance of blends containing toluene in an F-4 engine.



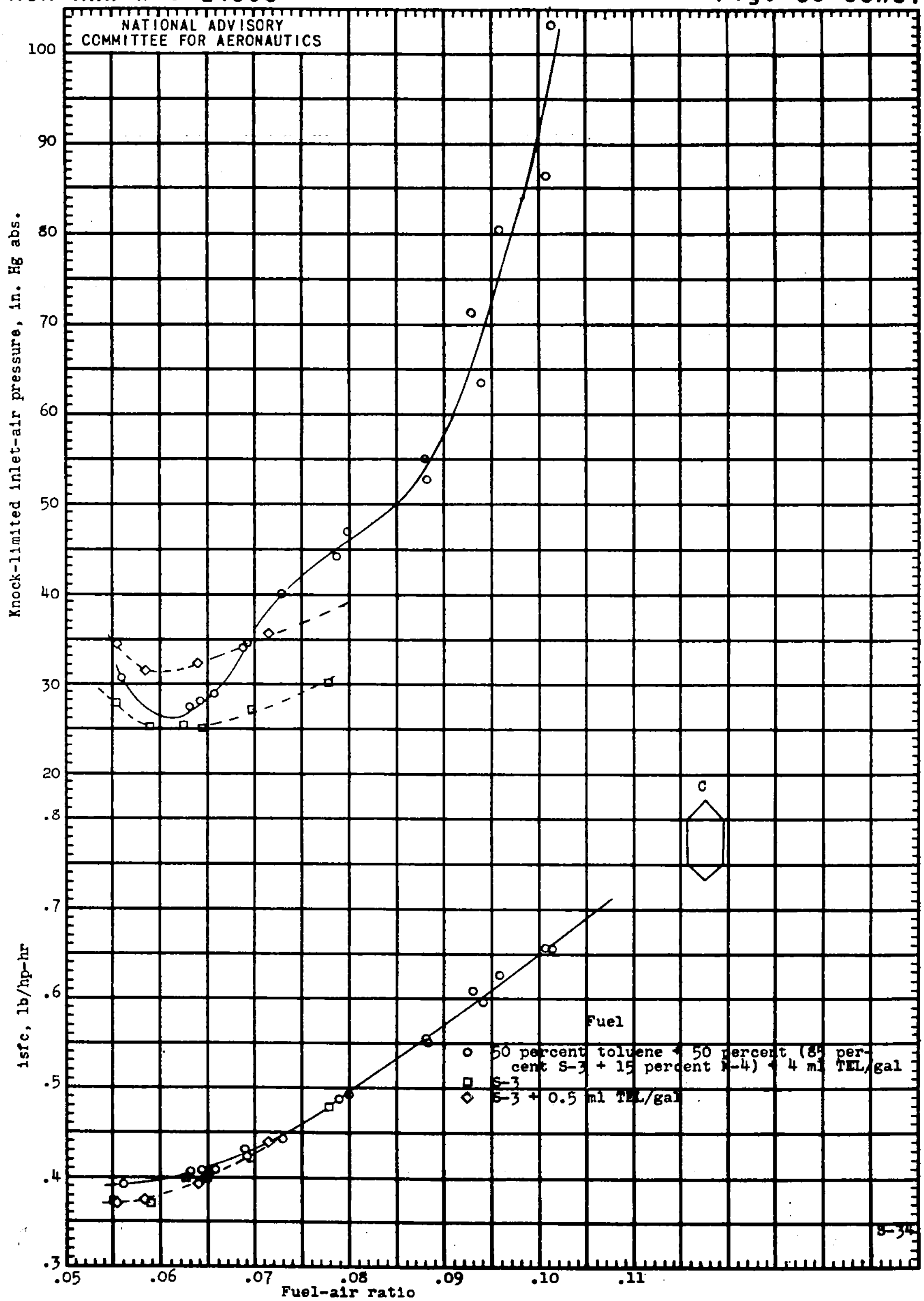
(b) 25 percent toluene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 8.-Continued.

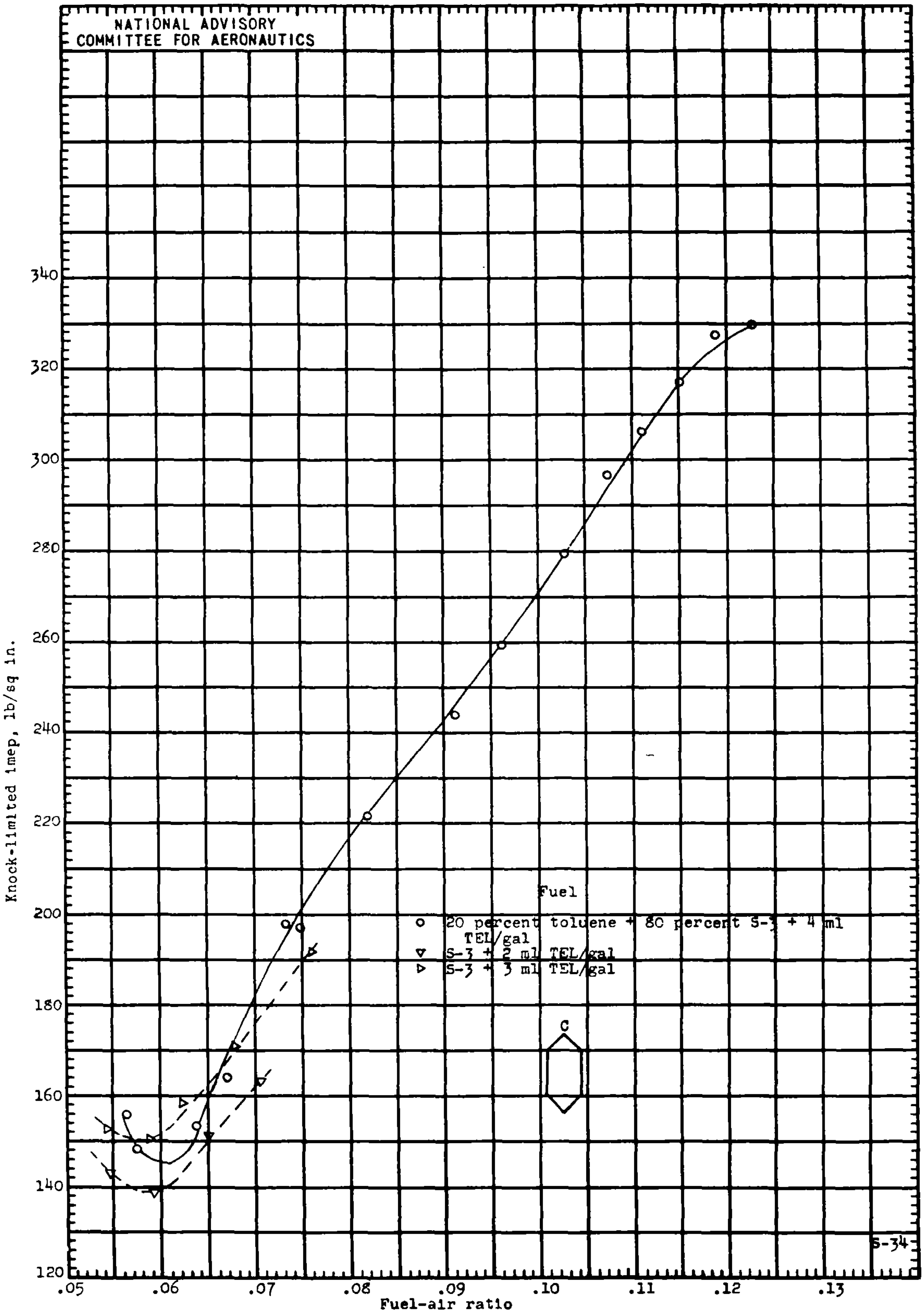


(c) 50 percent toluene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

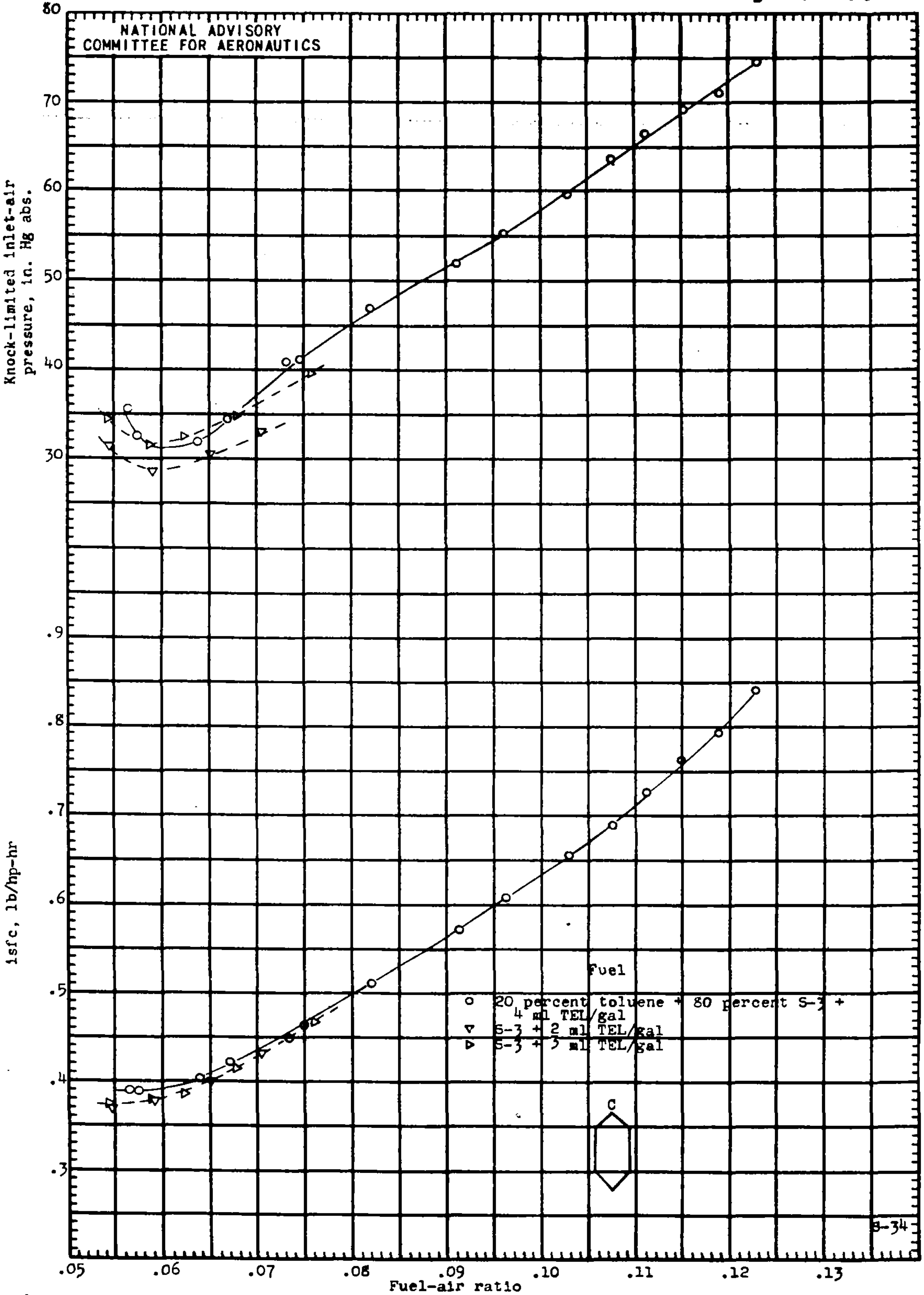
Figure 8. - Continued.



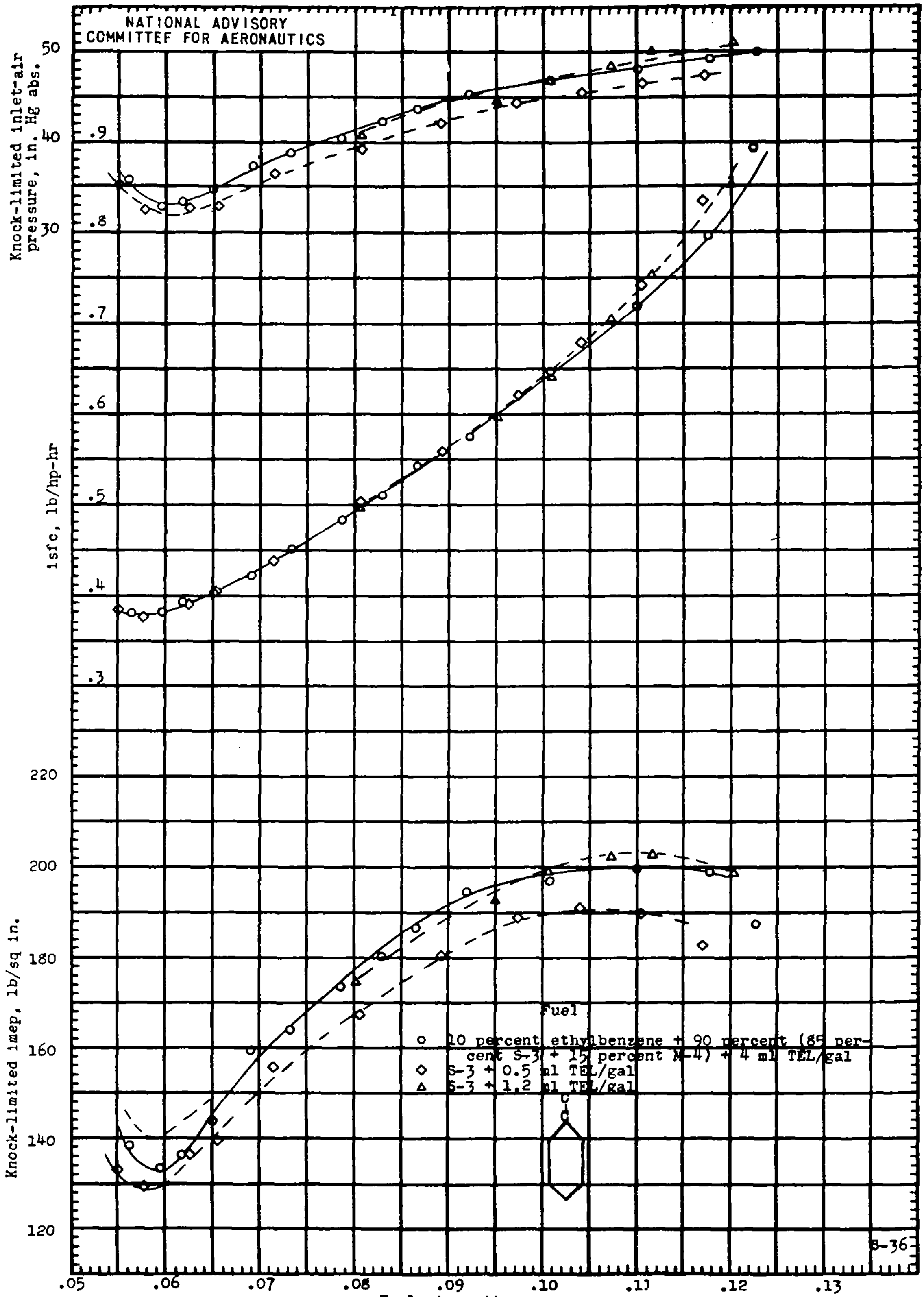
(c) Concluded.
Figure 8. - Continued.



(d) 20 percent toluene plus 80 percent S-3 plus 4 ml TEL per gallon.
Figure 8. - Continued.

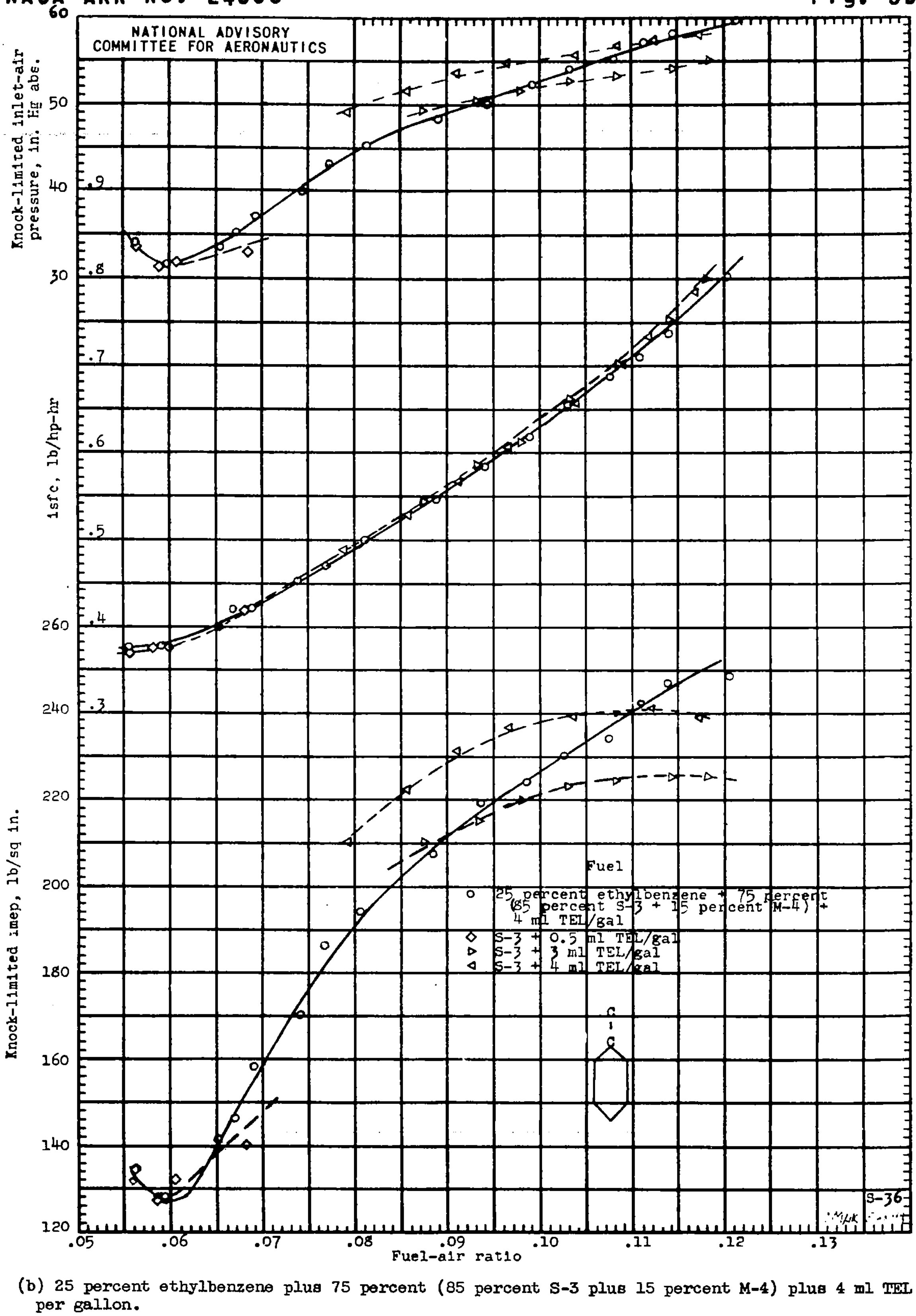


(d) Concluded.
Figure 8. - Concluded.

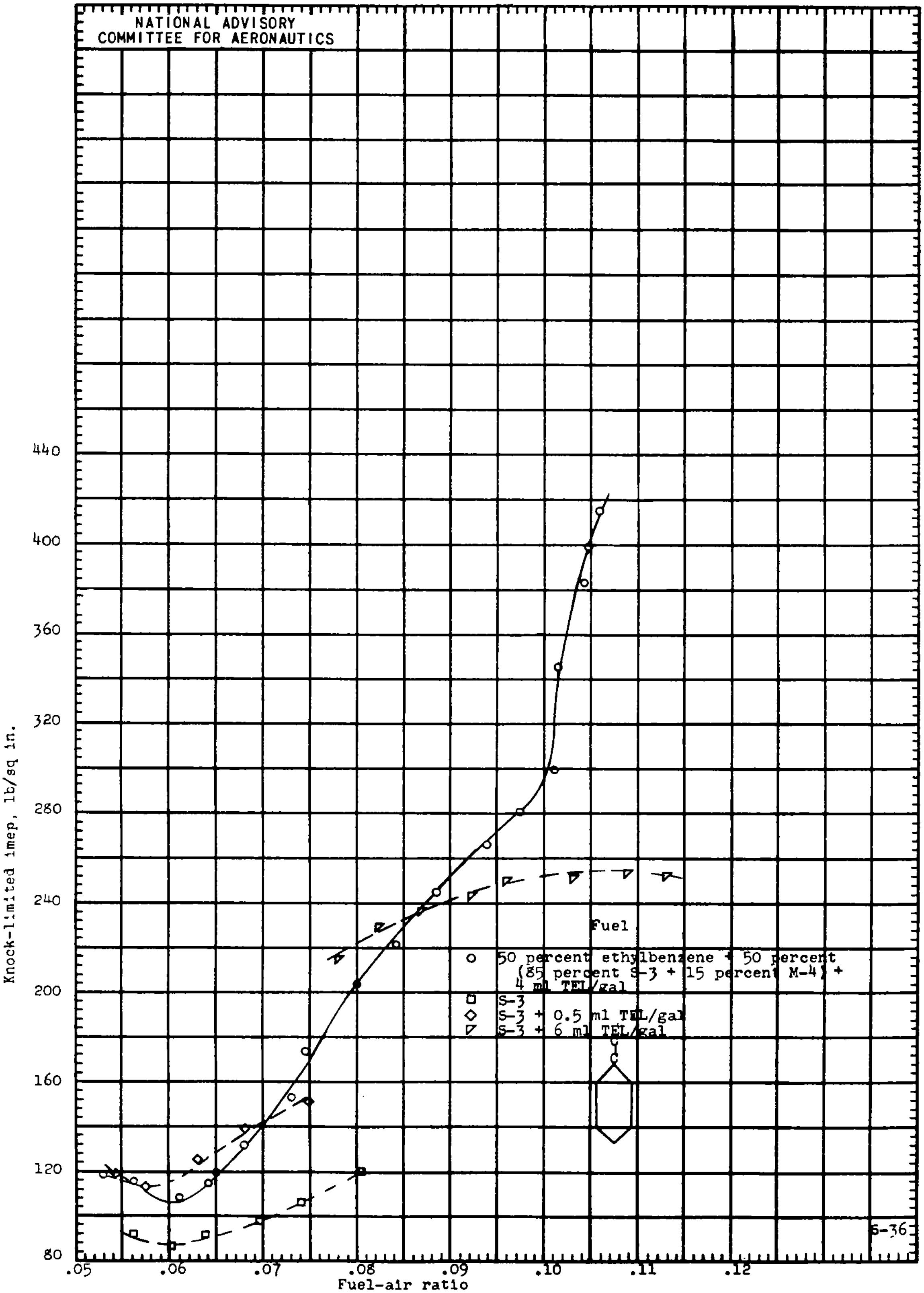


(a) 10 percent ethylbenzene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 9. - Knock-limited performance of blends containing ethylbenzene in an F-4 engine.

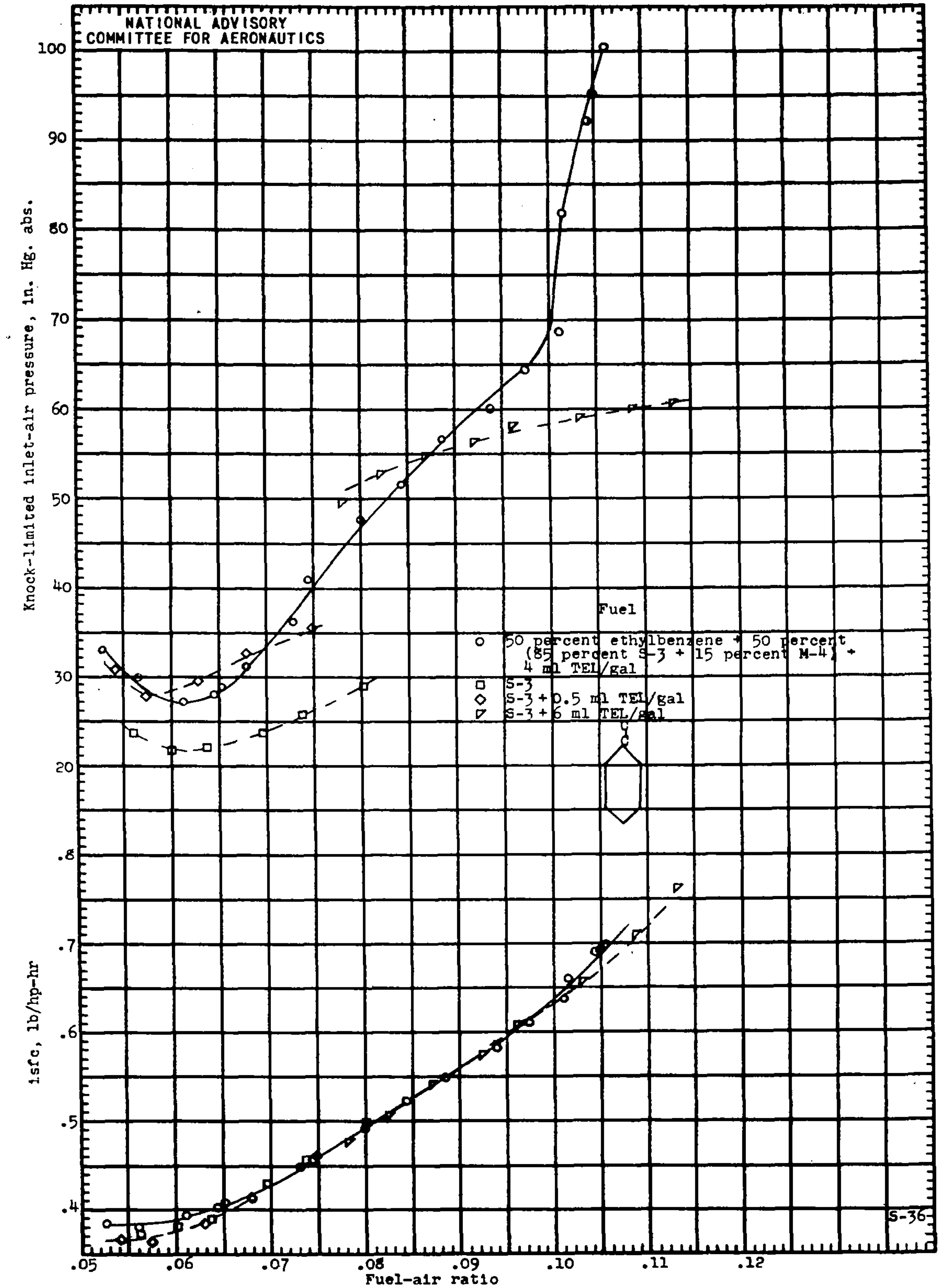


(b) 25 percent ethylbenzene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 9. - Continued.

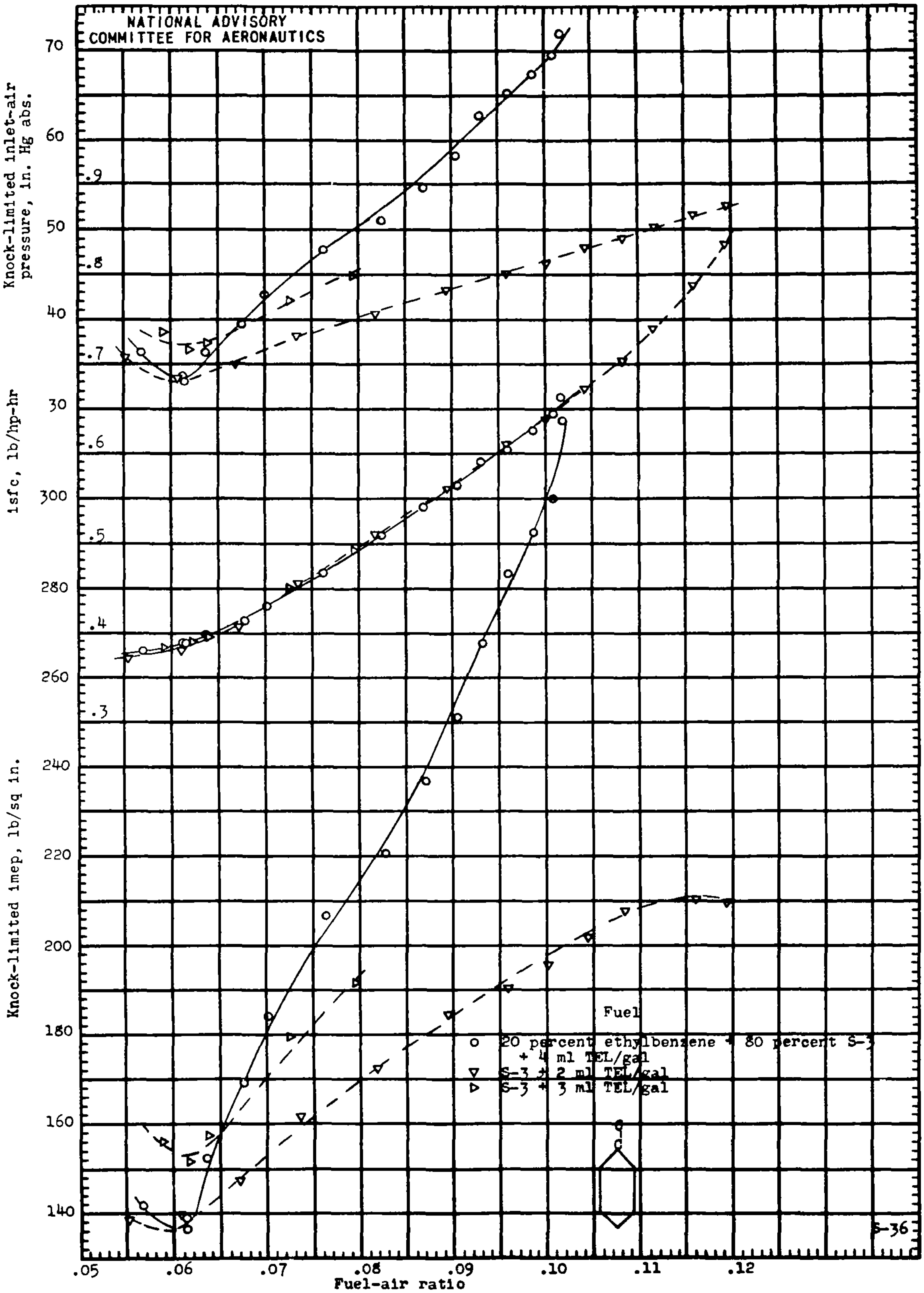


(c) 50 percent ethylbenzene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 9.-Continued.

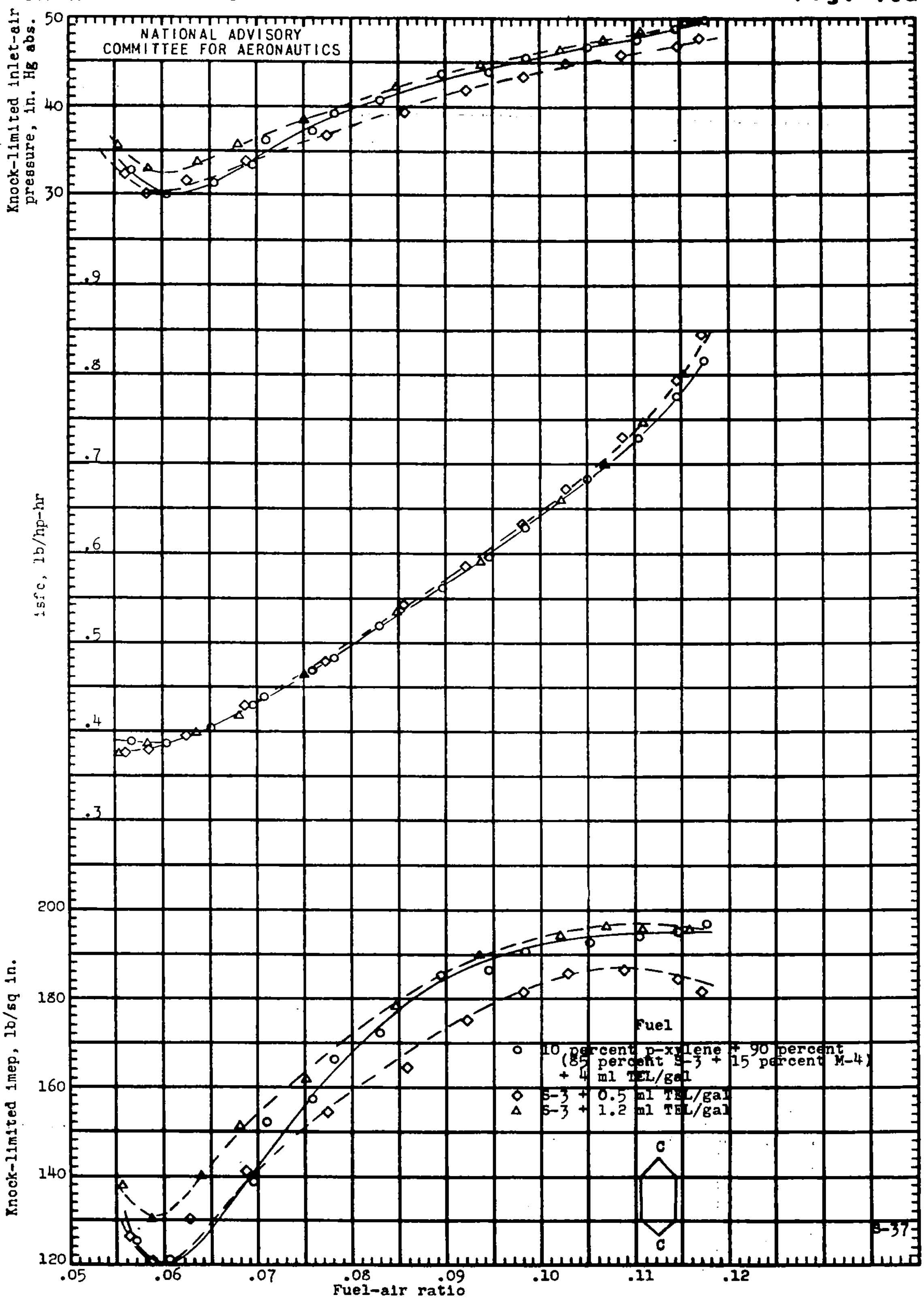


(c) Concluded.
Figure 9. - Continued.



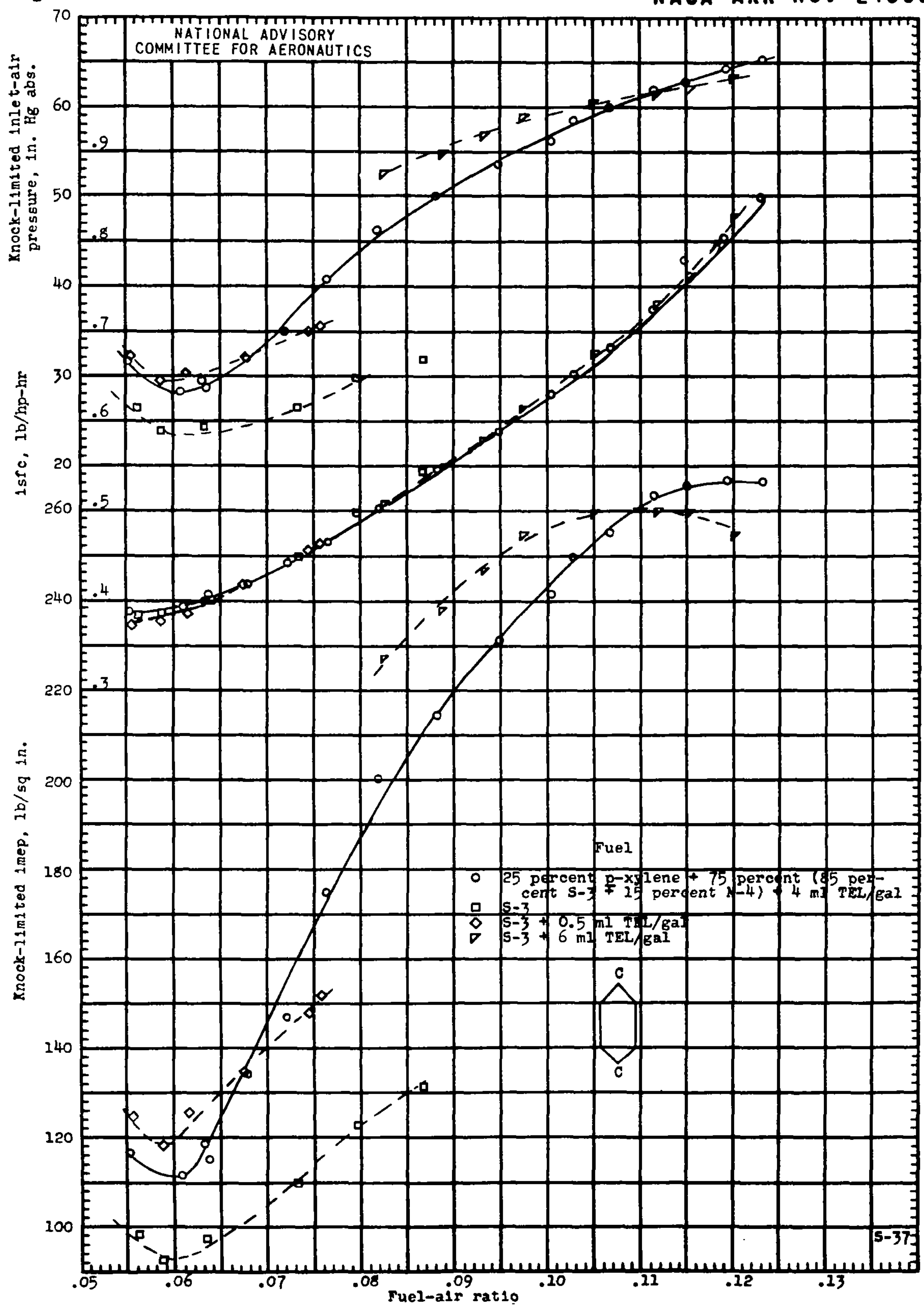
(d) 20 percent ethylbenzene plus 80 percent S-3 plus 4 ml TEL per gallon.

Figure 9. - Concluded.



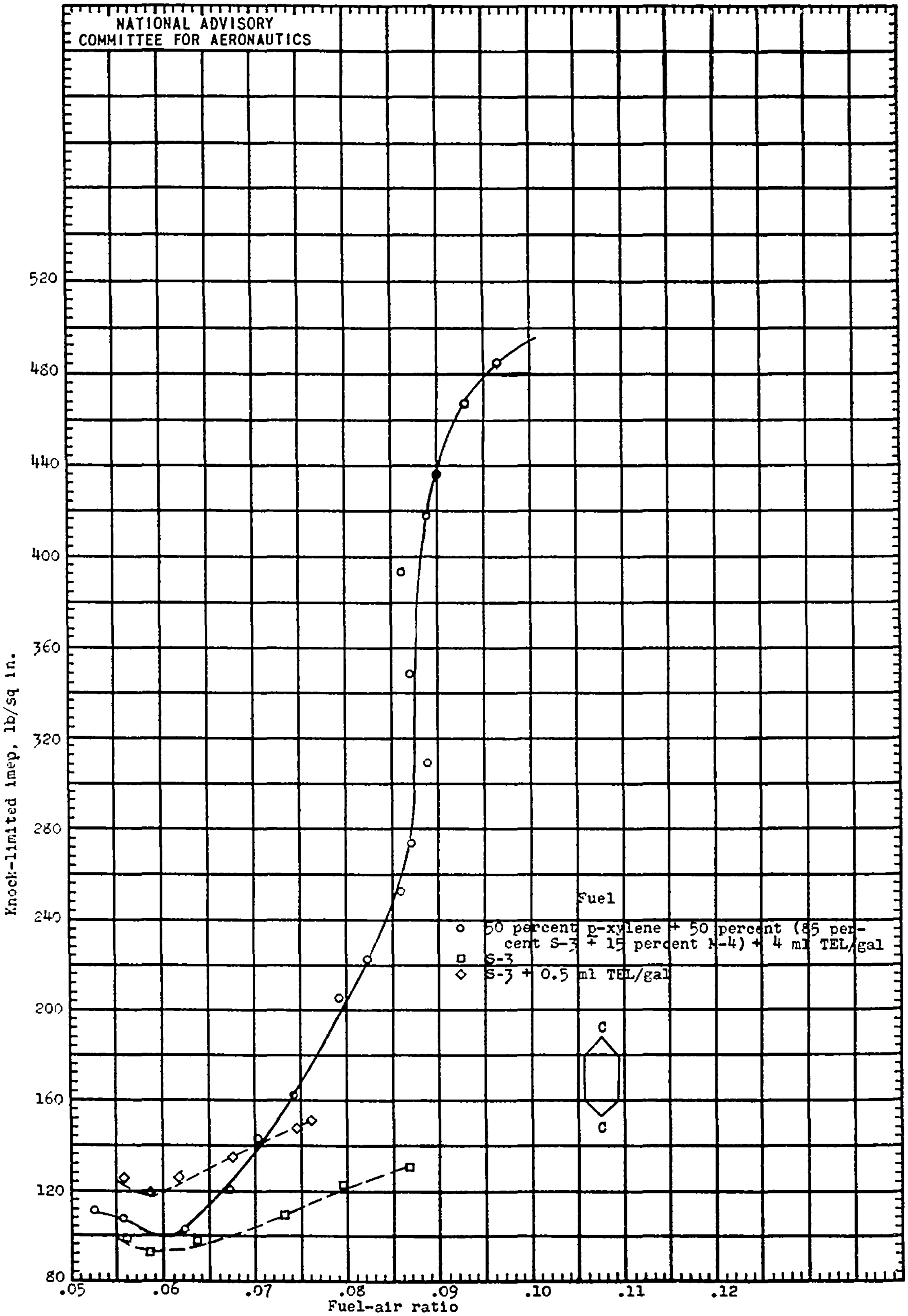
(a) 10 percent p-xylene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 10. - Knock-limited performance of blends containing p-xylene in an F-4 engine.



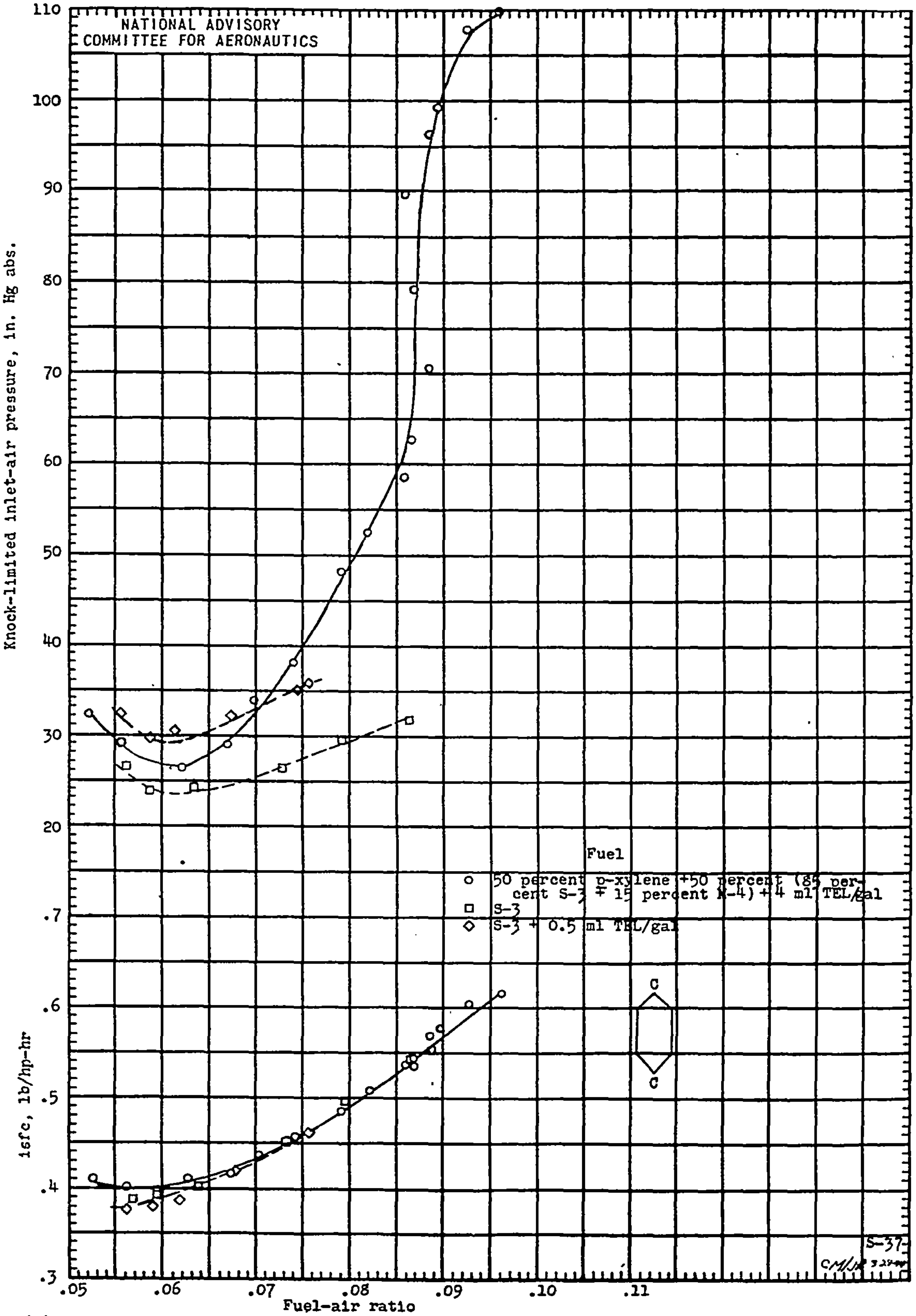
(b) 25 percent p-xylene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 10. - Continued.

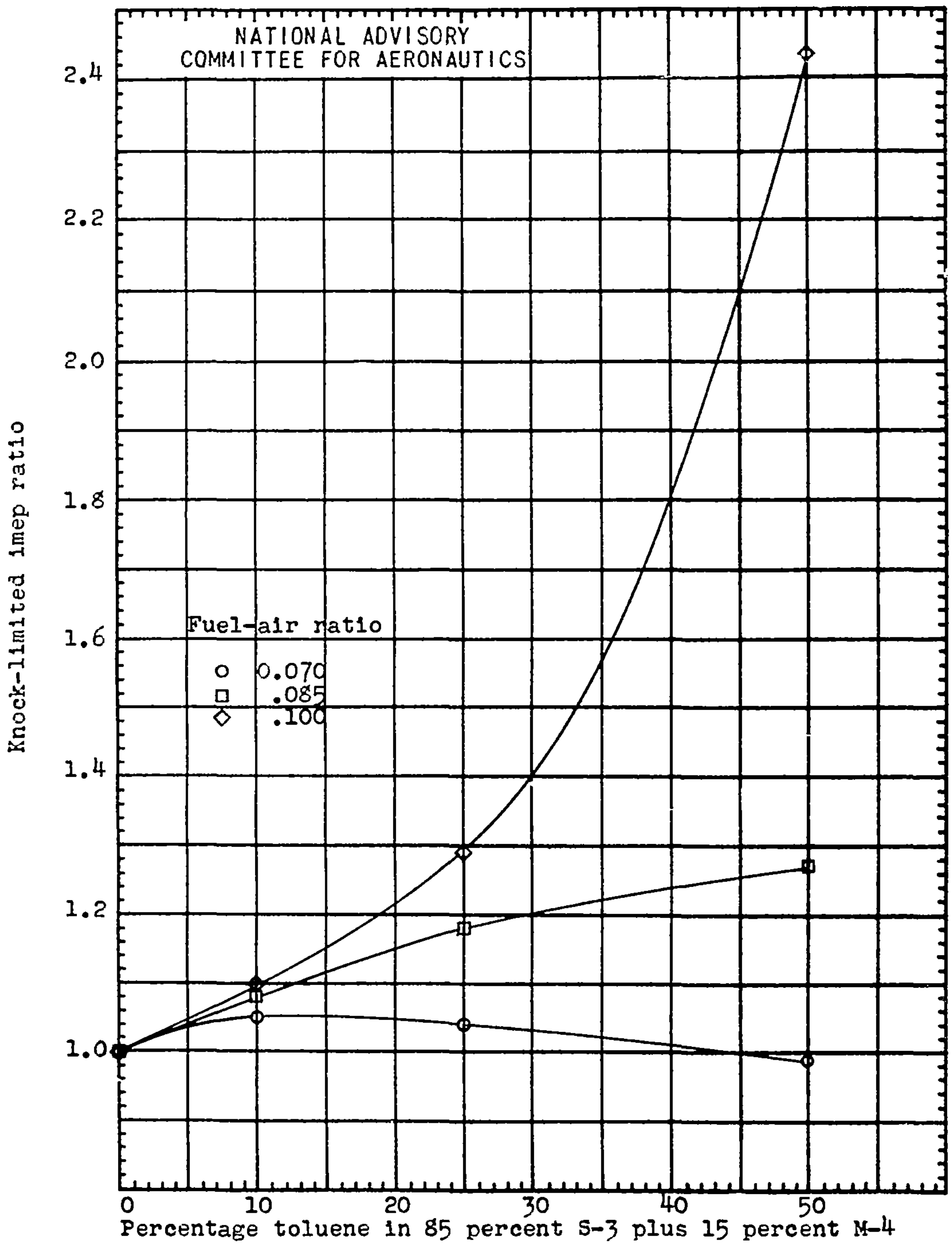


(c) 50 percent p-xylene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

Figure 10.-Continued.

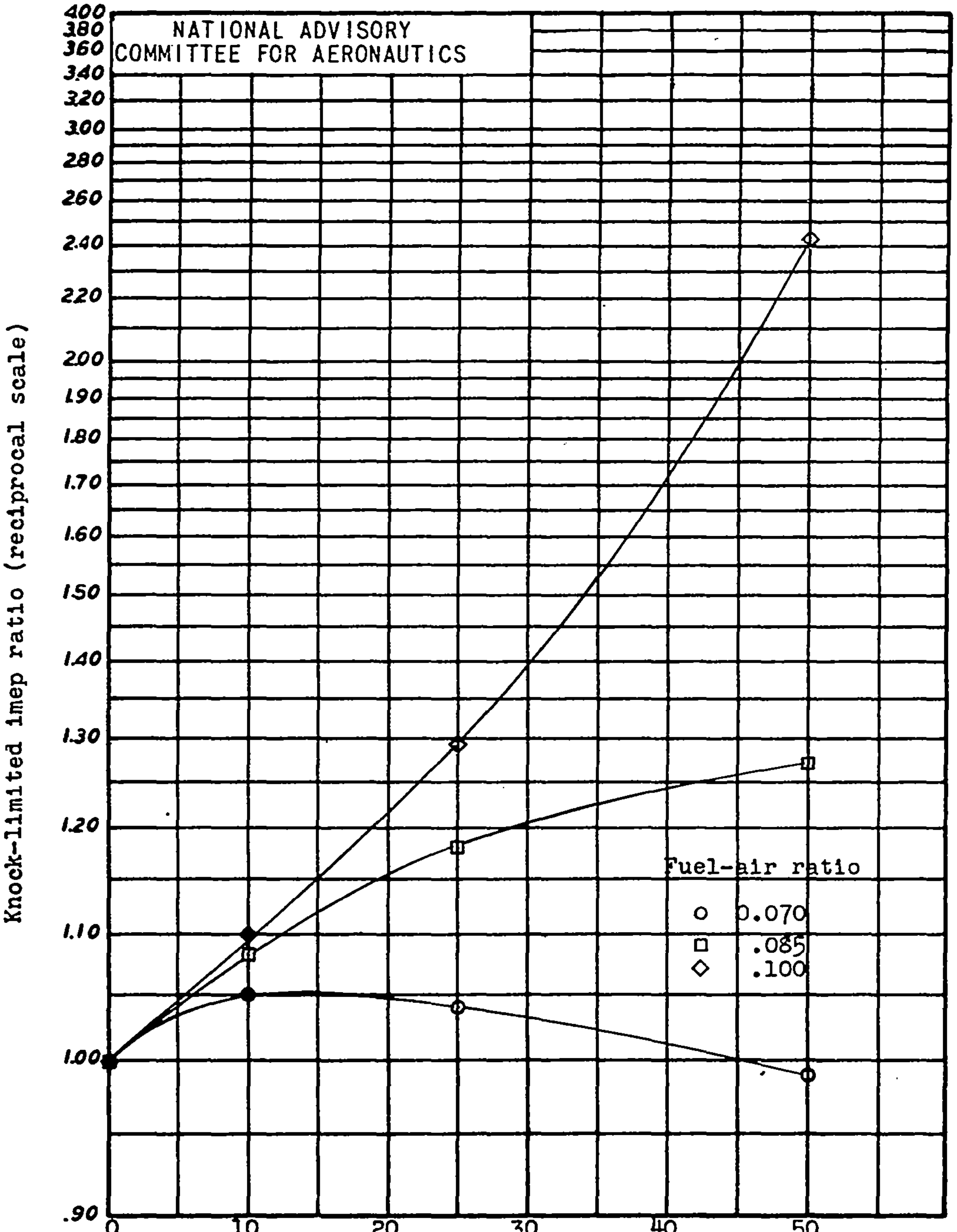


(c) Concluded.
Figure 10. – Concluded.



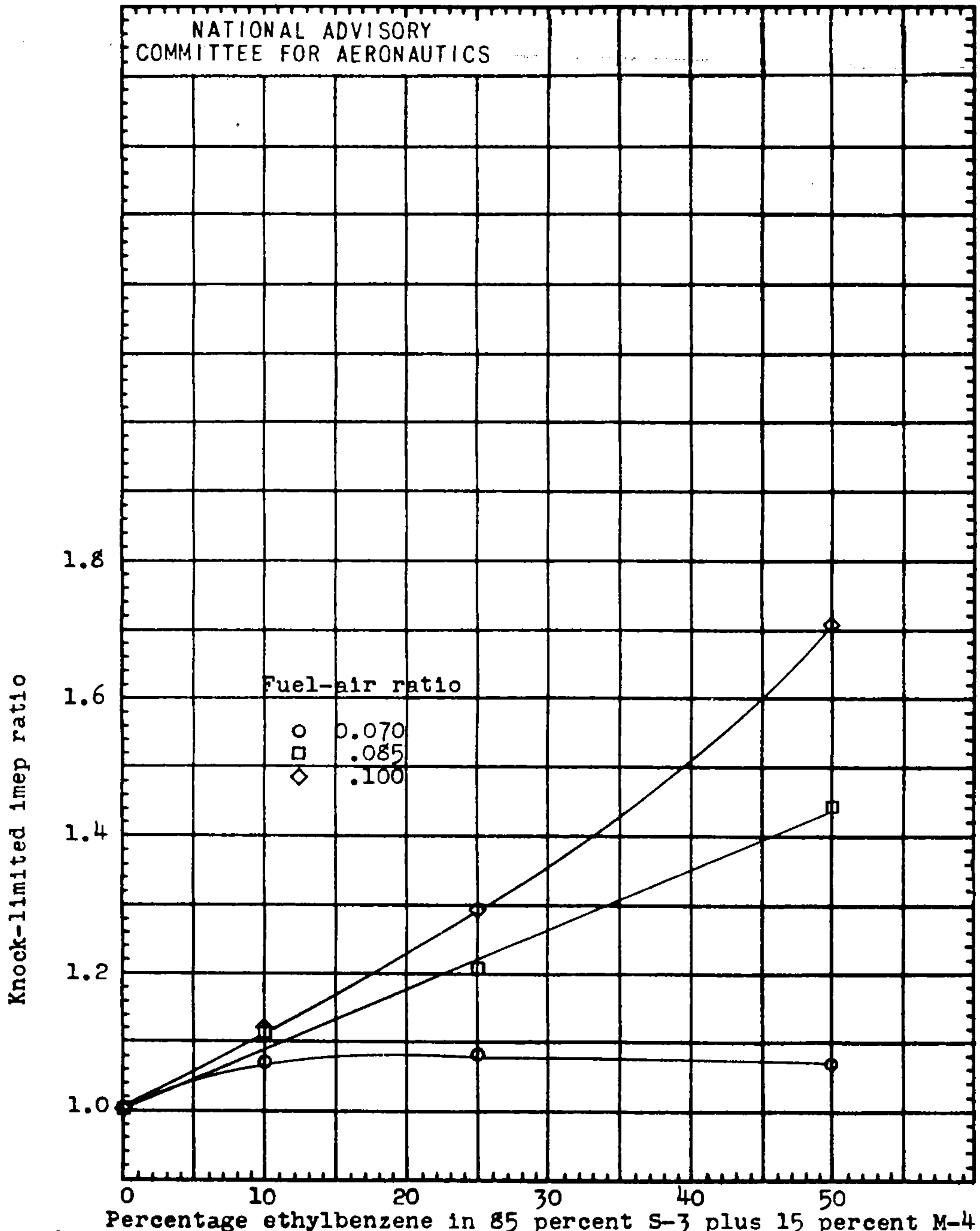
(a) Knock-limited imep ratio (linear scale).

Figure 11. - The blending sensitivity of toluene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.



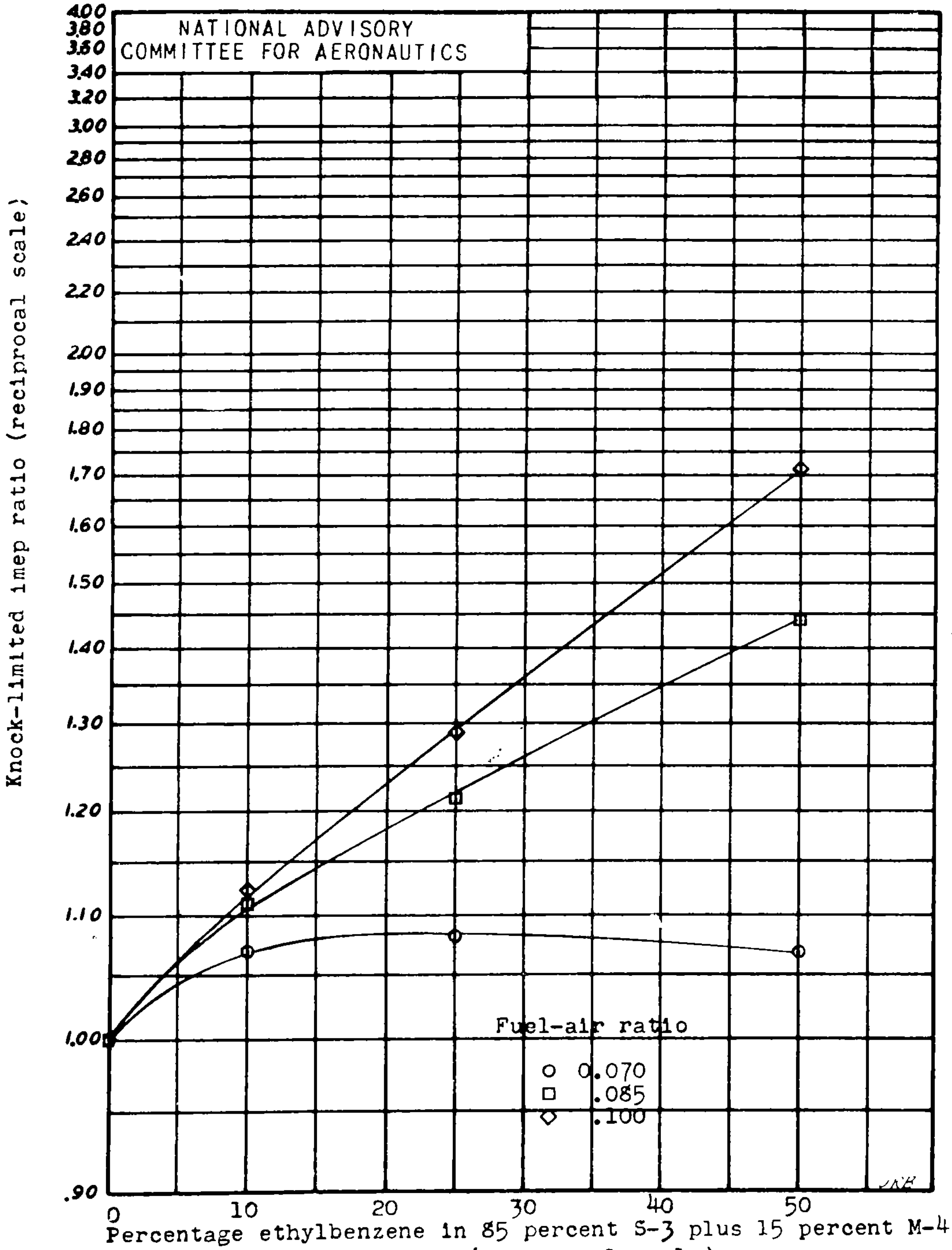
Percentage toluene in 85 percent S-3 plus 15 percent M-4

(b) Knock-limited imep ratio (reciprocal scale).
Figure 11. - Concluded.

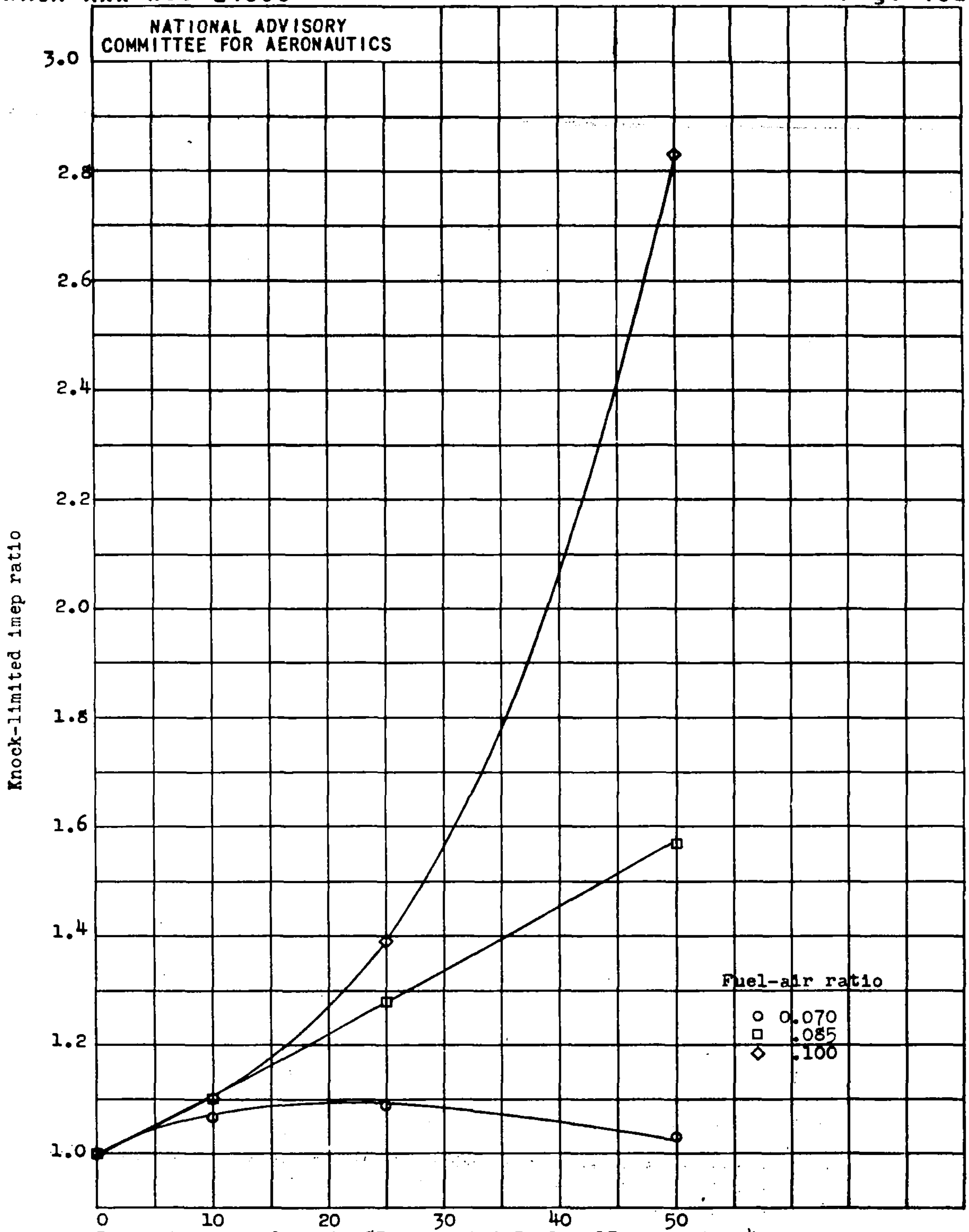


(a) Knock-limited imep ratio (linear scale).

Figure 12. - The blending sensitivity of ethylbenzene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.

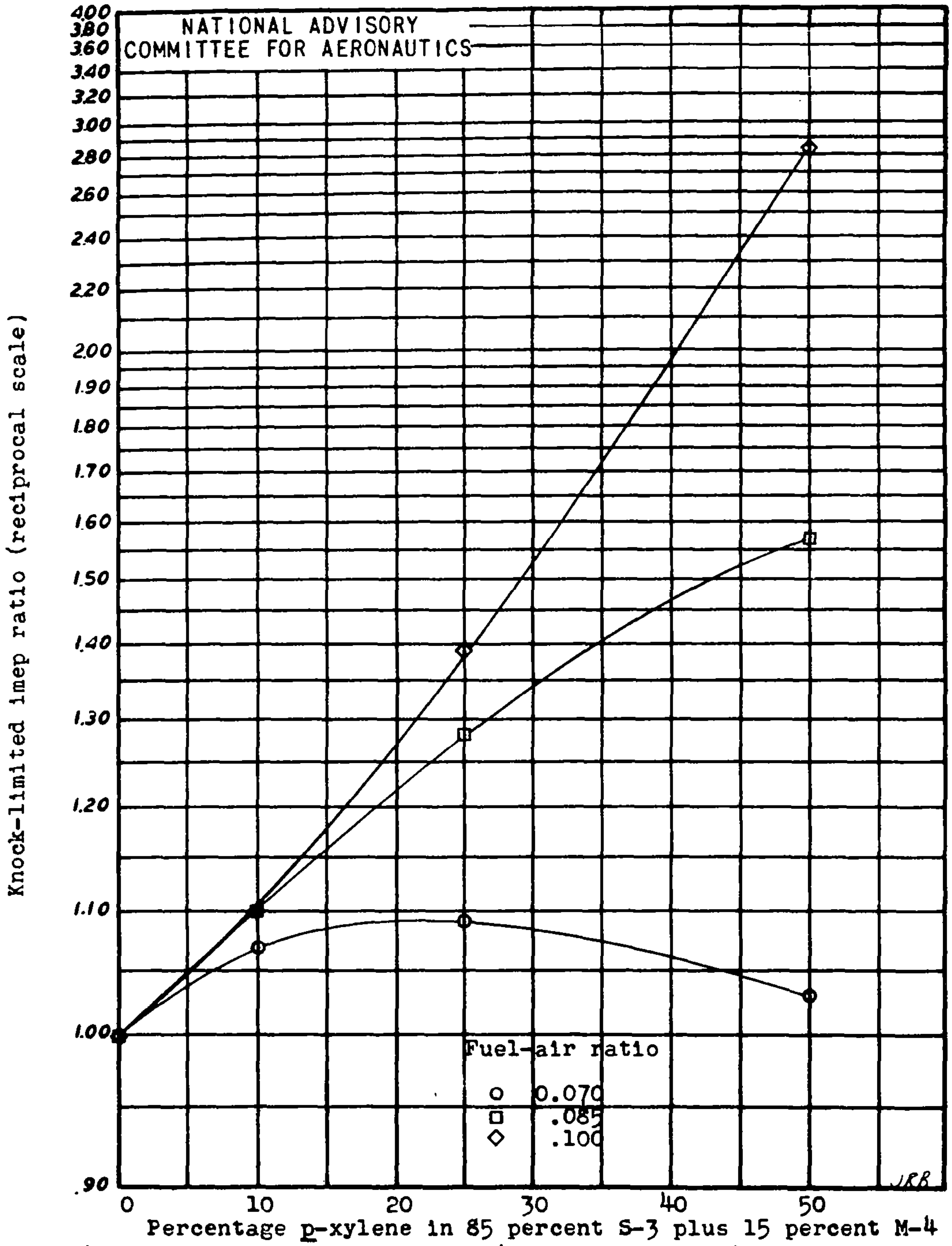


(b) Knock-limited imep ratio (reciprocal scale).
Figure 12. - Concluded.



(a) Knock-limited imep ratio (linear scale).

Figure 13. - The blending sensitivity of p-xylene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.



(b) Knock-limited imep ratio (reciprocal scale).
Figure 13. - Concluded.

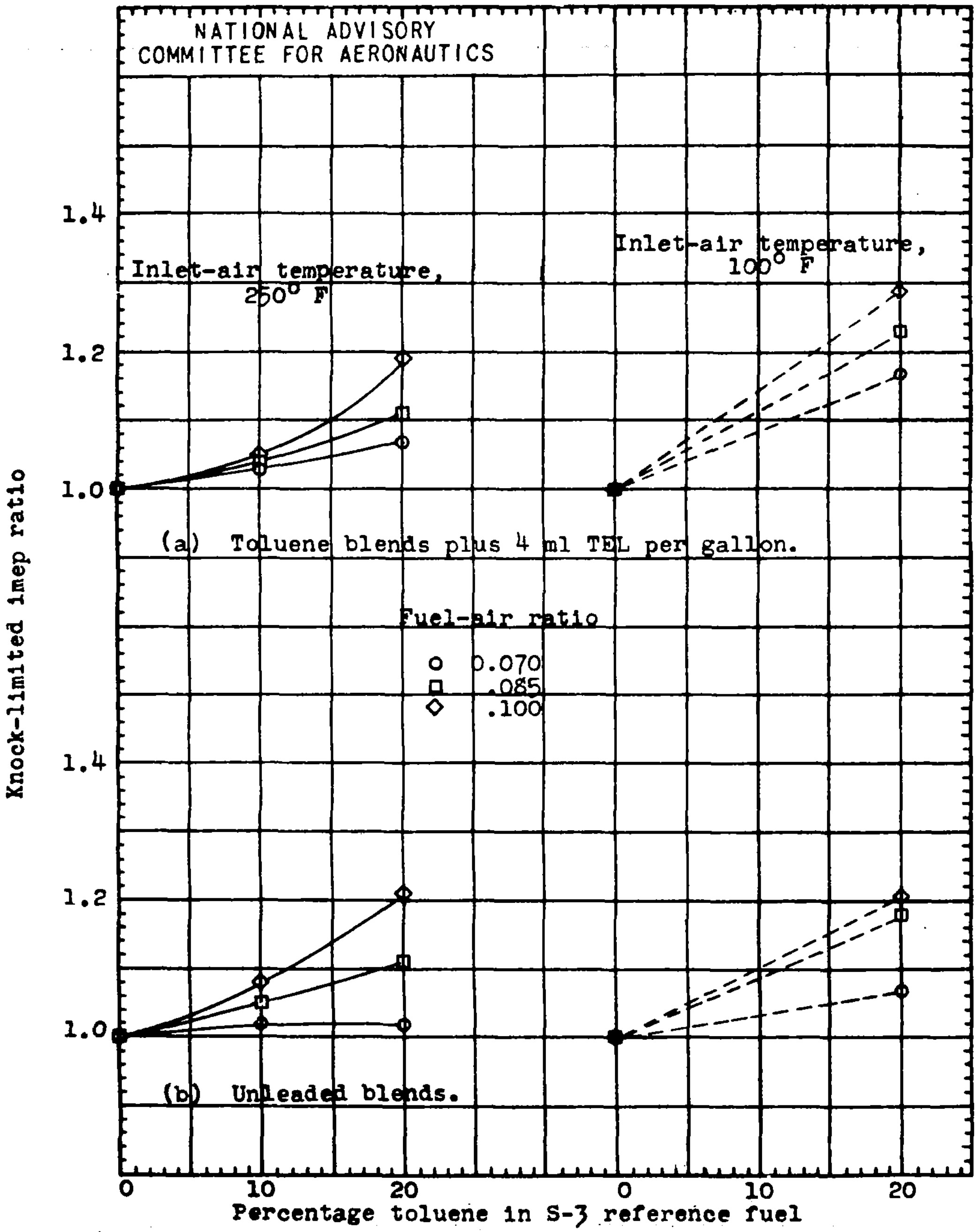


Figure 14. - The blending sensitivity of toluene in S-3 reference fuel. 17.6 engine.

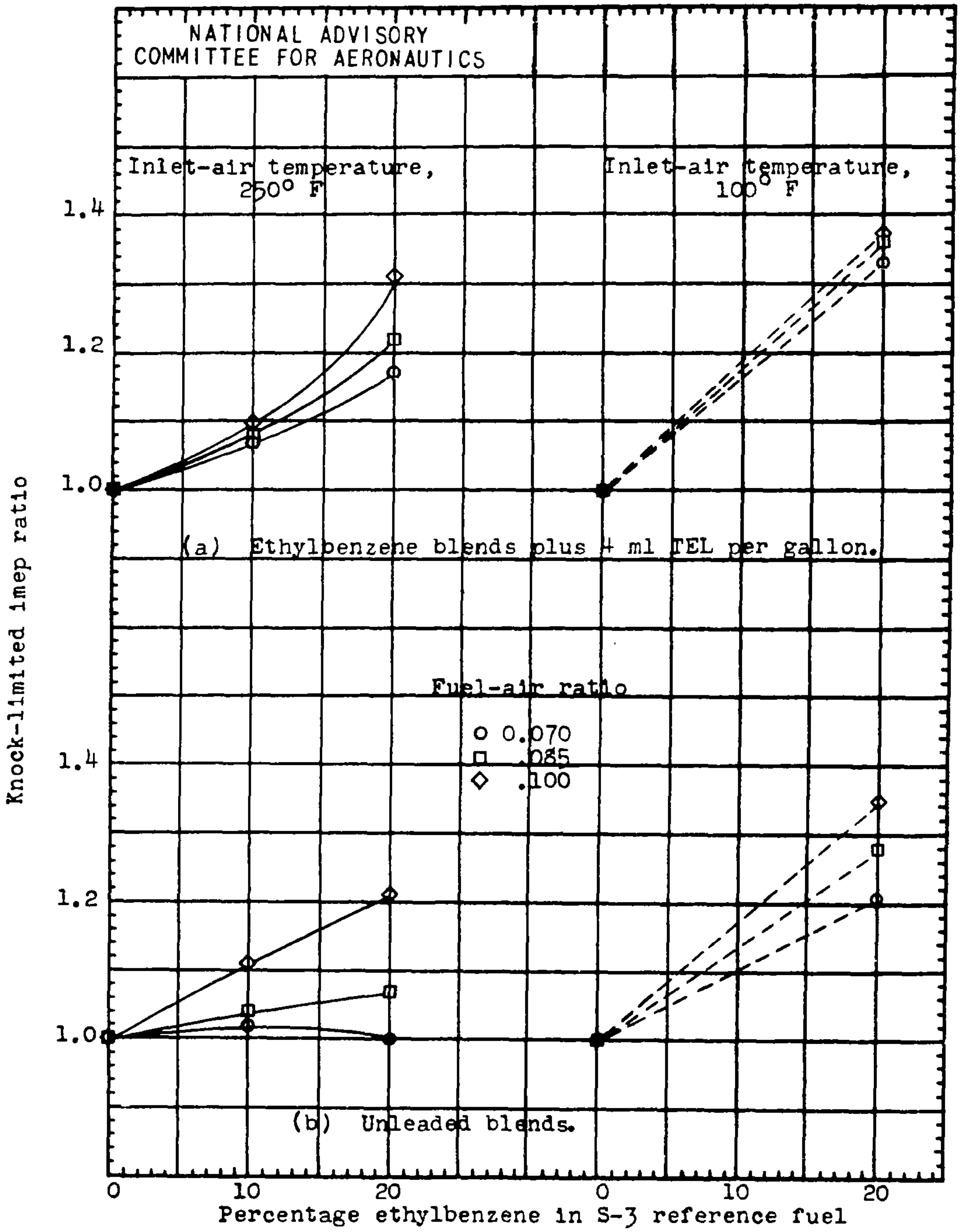


Figure 15. - The blending sensitivity of ethylbenzene in S-3 reference fuel. 17.6 engine.

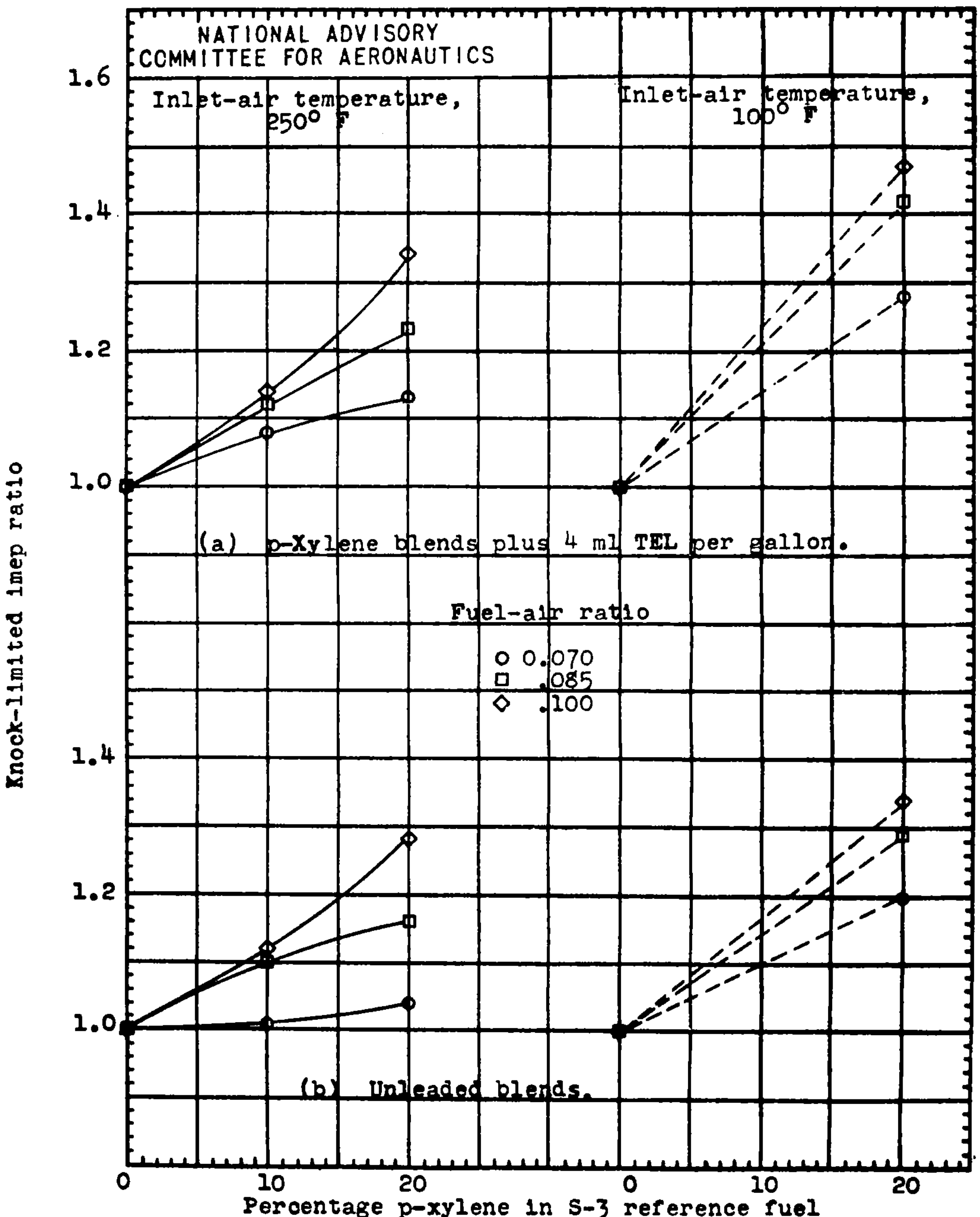


Figure 16. - The blending sensitivity of p-xylene in S-3 reference fuel. 17.6 engine.